

DEPARTMENT OF THE NAVY

PERFORMANCE ESTIMATES OF CAPTURED AIR BUBBLE VEHICLES
WITH WATER JET PROPULSION

by

Robert M. Williams

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SYMBOLS

^A j	jet area at exit, square feet
A _p	pump cross-sectional area, square feet
Ъ	beam of bubble, feet
$^{\mathrm{c}}_{\mathrm{D}_{\mathrm{e}}}$	coefficient of external aerodynamic drag $\left(\frac{1}{5(\ell/b)}\right)$
c _f	turbulent skin friction coefficient $ \left[0.482 \left(\log_{10} R_{\ell} \right)^{-2.618} + 0.0004 \right] $
c^{Γ}	coefficient of external aerodynamic lift
c ₁	correction factor for first-order estimate of wetted area associated with "additional sidewall depth" $(\ell_{\rm g}/\ell)$
c ₂	constant which regulates pump operation $(H_p/Q^2, for constant efficiency), sec^2/ft^5$
с ₆	equivalent wetted depth, feet (defined by (total wetted sidewall area average wetted sidewall length), where the numerator is the total immersed area of the sidewall when on the bubble, at zero speed and with no waves)
d _p	diameter of pump cross section, feet
D	drag nounde
	drag, pounds
D _c	discharge coefficient (Q/S _g V _c)
D _c	
	discharge coefficient (Q/SgVc)
D _w	discharge coefficient (Q/S_gV_c) wavemaking drag
D _w D _e D _r	discharge coefficient (Q/S _g V _c) wavemaking drag aerodynamic drag
D _w D _e	discharge coefficient (Q/S _g V _c) wavemaking drag aerodynamic drag ram drag
D _w D _e D _r	discharge coefficient (Q/S _g V _c) wavemaking drag aerodynamic drag ram drag additional sidewall drag
D _w D _e D _r D _{s,a} D _{s,b}	discharge coefficient (Q/S _g V _c) wavemaking drag aerodynamic drag ram drag additional sidewall drag sidewall drag due to bubble

 H_D head loss in ducts and nozzles, feet $H_{dyn} \qquad \qquad \text{dynamic head at pump entrance } \left(\frac{Q^2}{2gA_p^2}\right) \text{, feet}$

H pump head rise, feet

 H_{spi} static pump head at inlet, feet

H_v vapor head, feet

h daylight gap (for ACV), feet

 h_a additional sidewall depth, feet (0.5 H + C_6)

Kn duct and nozzle loss coefficient

 $\mathbf{K}_{\mathbf{D_n}}$ duct and nozzle design-speed loss coefficient

 K_{D} duct and nozzle static loss coefficient

K_I total internal head loss coefficient

 K_{L_n} design internal head loss coefficient

k velocity ratio $\left(\frac{v_j - v}{v} = \frac{\Delta v}{v}\right)$

 $k_{\scriptsize \mbox{\scriptsize opt}}$ optimum velocity ratio for maximum efficiency

L lift, pounds

length of bubble, feet

 $\frac{L}{b}$ length/beam ratio (bubble)

L wetted sidewall length, feet

n number of wetted sides

 q_a dynamic pressure of air $(q_a \approx 0.0012 q_w)$, $1b/ft^2$

 q_{w} dynamic pressure of water $(2.85 V_{k}^{2})$, $1b/ft^{2}$

P pressure of the central pressure distribution in the sequence of images, 1b/ft²

P_R power required, 1b-ft/sec

```
volume flow rate, ft3/sec
Q
R_{\ell}
           Reynolds number (1.30 \text{ V}_{k} \text{£} \times 10^{5})
           bubble area, ft2
S
           air gap area (ACV), ft2
           thrust (= drag). pounds
T
V
           forward velocity, ft/sec
           design forward velocity, ft/sec
v,
           exit velocity, ft/sec
           forward velocity, knots
v_k^{/\sqrt{\ell}}
           speed/length parameter
           weight, pounds
           specific weight (W/S), 1b/ft2
           specific cushion loading, 1b/ft3
           pressure/length parameter, 1b/ft3 (pressure of bubble
            region (w) ÷ length of bubble (1))
           pump efficiency
           propulsive efficiency
           density of air, slugs/ft3
           density of water, slugs/ft3
Pw
           cavitation index
σ
```

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SUMMARY

Performance predictions of Captured Air Bubble (CAB) vehicles utilizing water jet propulsion are presented. The analysis was made for various combinations of gross weight, specific leading, length-to-beam ratio, and wave height. In addition, the effect of varying the ducting loss coefficient has also been investigated.

It was found that the total drag "hump" of low length-to-becm ratios (l/b) was eliminated at higher L/b values. This effect is due to the complex behavior of the wavemaking drag component. It was further found that for a particular length-to-beam ratio (l/b), a value of specific cushion loading existed which optimized the performance (as measured by the ratio of weight to horsepower required). The lighter specific cushion loadings offered definite performance advantages at the lower length-to-beam ratios.

INTRODUCTION

Current interest in CAB vehicles has been based almost exclusively on estimates of their high-speed performance. As the theory upon which these estimates are based is updated by additional research, it is necessary from time to time to modify the original performance predictions. This report employs the most recent theory available (References 1, 2, and 3), programmed for an IBM 7090/SC-4020 computer-plotter combination. It is felt that the results presented here represent the most complete and reliable predictions available at this time.

ANALYSIS

The computer model calculates CAB performance by determining drag and power requirements at specified increments of the speed/length parameter, $V_{\bf k}/\sqrt{\chi}$.

The important program inputs are: vehicle gross weight, length-to-beam ratio (ℓ/b), specific cushion leading parameter, w/\sqrt{s} , sidewall factors C_1 and C_6 , configuration aerodynamic lift coefficient C_1 , water

jet pump efficiency η_e , and duct and nozzle loss coefficient K_D . Pertinent combinations of these design parameters have been plotted and analyzed in this report. The tabulated variation is given in Table 1.

An exact formulation of the wave drag theory of Reference 2 has been incorporated into the program. However, the values on the sub-hump side are faired to a slope of 2.0 (on log-log paper), as shown in Figure 1; and secondary humps have been neglected. This fairing is essentially arbitrary, although it does agree reasonably well with the small amount of experimental data available. Experiments are presently being undertaken to ascertain the validity of this drag theory and that of Reference 1 for CAB vehicles of various length-to-beam ratios, with emphasis on the values of wavemaking drag in the sub-hump region.

The advantages of water jet propulsion in CAB applications are numerous; e.g., higher propulsive efficiencies are more readily obtainable at high speeds than is the case with conventional propellers. Since inlets and exhausts are located at or below the water line, there is relatively little potential energy loss or water weight penalty incurred (as in a hydrofoil application). Noise propagation will be less than with conventional propulsors. Debris and shallow water problems are minimized, since the entire unit may be given a low-profile configuration, particularly if multiple pump arrays are used. A variable-area intake and exit will permit large flow rates at low speeds, thus providing sufficient thrust for rapid acceleration.

Pump efficiencies of 90 percent are considered feasible for water jets. With this assumption, the propulsive efficiency $\left(\eta_p\right)$ becomes dependent on the duct loss coefficient $\left(K_D\right)$ and velocity ratio $k = \left(\frac{V_j - V}{V}\right).$ The value of k may be optimized to give maximum η_p at a given design condition of wave height and velocity. The value of K_D is a function of the flow-through velocity and the particular ducting system utilized to channel the water to and from the pumps.

BASIC CAB PERFORMANCE EQUATIONS

The following equations are given as a concise summary of the theory developed in References 1 and 2.

(a) Wavemaking Drag (Figure 1)

$$\frac{D_{w}}{W} = \left[\left(\frac{w}{\ell} \right)^{2} \left(1 - 0.0012 \ C_{L} \frac{q_{w}}{w} \right)^{2} \frac{\ell^{3}}{\rho_{w}^{2} \ell} \right] \left(\frac{\rho_{w}^{2} \ell}{P_{o}^{2} \ell} \right)$$

where $\frac{\rho_w gD}{P_o^2 L}$ is computed for a channel of infinite depth and width equal to ten times the bubble length by the following formula:

$$\frac{\rho_{w}gD}{P_{o}^{2} \ell} = 4 \gamma \left\{ \left(\frac{\beta}{\gamma} \sin \Omega \right)^{2} + \frac{1}{4N\pi^{2}} + \frac{1}{\pi^{2}} \sum_{n=1}^{N} \frac{1}{n^{2}} \left[1 + \frac{1}{\sqrt{1 + \left(\frac{2\pi n}{\gamma} \right)^{2}}} \right] \right\}.$$

$$\sin^2\left(n\pi\frac{\beta}{\gamma}\right) \cdot \sin^2\left[\Omega\sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1 + \left(\frac{2\pi m}{\gamma}\right)^2}}\right]$$

In the above equation, the following definitions apply:

$$\beta = \frac{\text{bubble width}}{\ell} = \frac{1}{\ell/b}$$

$$\gamma = \frac{\text{width of channel}}{\ell} = 10$$

$$\Omega = \frac{g\ell}{2v^2}$$

The summation of the above equation is transmitted when

$$\frac{1}{n} \left[1 + \frac{1}{\sqrt{1 + \left(\frac{2\pi n}{\sqrt{\Omega}}\right)^2}} \right] \le 0.001$$

The values of $\frac{\rho_w gD}{P_o^2 L}$ versus $\frac{V}{\sqrt{g \sqrt{s}}}$ on the pre-hump side are then altered to a slope of 2 on log-log paper.

(b) Additional Sidewall Drag:

$$\frac{D_{s,a}}{W} = n \left(\frac{\ell}{b}\right) C_1 C_f \left(\frac{h_a}{\ell}\right) \frac{q_w}{w}$$

(c) Sidewall Drag Due to Bubble:

$$\frac{D_{8_2b}}{W} = \left(\frac{\ell}{b}\right) \quad C_1 \quad C_f \quad \left(\frac{q_w}{w}\right) \left[\frac{D_w}{W} - \frac{h}{\ell}\right]^2 \quad \frac{1}{\frac{D_w}{W}} \quad , \quad \sqrt{\ell} \geq K$$

or

$$\frac{D_{s,b}}{W} = \left(\frac{\ell}{b}\right)C_1 C_f \left(\frac{q_w}{w}\right)\left[\left(\frac{D_w}{W}\right)_{max} - \frac{h}{\ell}\right]^2 \left(\left(\frac{D_w}{W}\right)_{max}\right), \quad \frac{V_k}{\sqrt{\ell}} < K$$

where K is the value of $V_k/\sqrt{\ell}$ taken at the wave drag "hump" $\left(\frac{D_w}{W}\right)_{max}$ for a specified ℓ/b .

(d) Aerodynamic Drag:

$$\frac{D_e}{W} = C_{D_e} \frac{q_a}{W}$$

(e) Trunk Drag:

$$\frac{D_{t}}{W} = 0.00792 \left(\frac{H - 2h}{L} \right)^{1.2} \frac{q_{w}}{W} \cdot \left(\frac{b}{b + L} \right)$$

(f) Ram Drag:

$$\frac{D_r}{W} = 2 D_c \left(1 - C_L \frac{q_a}{w} \right)^{\frac{1}{2}} \left(\frac{q_a}{w} \right)^{\frac{1}{2}} \left(\frac{s_g}{s} \right)$$

(g) Total Drag:

$$\frac{D}{W} = \frac{D_{w}}{W} + \frac{D_{3,8}}{W} + \frac{D_{s,b}}{W} + \frac{D_{c}}{W} + \frac{D_{t}}{W} + \frac{D_{r}}{W}$$

(h) Propulsive Power-to-Weight Ratio:

$$\frac{\mathbb{P}_{\mathbf{p}}}{\mathbf{w}} = \left(\frac{\mathbf{D}}{\mathbf{w}}\right) \frac{\mathbf{v}_{\mathbf{k}}}{326 \, \mathbb{N}_{\mathbf{p}}}$$

(i) Cushion Power-to-Weight Ratio:

$$\frac{H_c}{W} = 0.14 \left(\frac{D}{W}\right) \frac{V_k}{326}$$

(j) Weight-to-Horsepower Ratio:

$$\frac{W}{H} = \left[\frac{H_P}{W} + \frac{H_C}{W} \right]^{-1}$$

(k) Specific Power:

$$\frac{P_R}{WV} = \frac{326}{V_L (W/H)}$$

BASIC WATER JET EQUATIONS

As previously noted, the water jet model used in the analysis was a variable-geometry configuration for which the theory discussed in Reference 3 is appropriate. A parabolic variation of $K_{\overline{D}}$ with $V/V_{\overline{D}}$ was assumed for the duct system with the design value of $K_{\overline{D}}$ remaining constant at values of $V/V_{\overline{D}} > 1.0$ (Figure 2).

The pumps were assumed to be capable of continuous operation at 90 percent efficiency η_e , while conforming to a pump head/flow rate relationship of $H_p = C_2 \ Q^2$. The constant C_2 is defined at a specified design speed and wave height and remains constant at all off-design conditions. The procedure for determining C_2 and other design constants is as follows:

An optimum value of the velocity ratio, $k = \frac{V_1 - V}{V} = \frac{\Delta V}{V}$, is determined by computing the optimum total internal loss coefficient at design conditions:

(a)
$$K_{L_D} = \left[1 - \frac{1}{\left(1 + k_{opt}\right)^2}\right] \cdot \frac{1 - \eta_e}{\eta_e} + \frac{K_{D_D}}{\eta_e}$$

where the value $k_{opt} = \sqrt{\frac{K_L}{(1 + K_L)}}$ is determined by an iterative process. The following computations of design values are then made:

(b) Flow Rate at Design Speed:

$$Q_D = D_D/(k_{opt} V_D \rho_w)$$

(c) Exit Velocity:

$$V_{j_D} = V_D (k_{opt} + 1)$$

(d) Thrust:

$$T_{D} = D_{D} = -\rho_{w} Q_{D} (V_{J_{D}} - V_{D})$$

(e) Pump Head:

$$H_{p_{D}} = \frac{\left(1 + \kappa_{D_{D}}\right) v_{j_{D}}^{2} - v_{D}^{2}}{2g}$$

(f) Total Exit Area:

$$A_{j_{D}} = \frac{Q_{D}}{V_{j}} = Q_{D} \sqrt{\frac{1 + K_{D_{D}}}{2g H_{p_{D}} + V_{D}^{2}}}$$

(g) Pump Constant $(H_p = C_2 Q^2)$

$$c_2 = \frac{H_{p_D}}{Q^2} = \frac{1 + K_{p_D}}{2g A_{j_D}^2} - \frac{V_{p_D}^2}{2g Q_{p_D}^2}$$

(h) The Efficiency is given by:

$$\eta_{p_{D}} = \frac{2 K_{D}}{\left(1 + k_{opt}\right)^{2} \left(1 + K_{L_{D}}\right)^{-1}} = 1 - k_{opt}$$

(i) The Shaft Horsepower is given by:

$$SF = \frac{D_D V_D}{550 \eta_D}$$

and the pump diameter is determined by the empirical relation:

$$d_{p} = \sqrt{\frac{SP}{1000}}$$

After the design values have been determined, the program determines the off-design performance by computing for each increment of velocity the following variables:

(j) Duct Loss Coefficient (Figure 2):

$$K_D = \left(K_{D_S} - K_{D_D}\right)\left(\frac{V}{V_D} - 1\right)^2 + K_{D_D}$$

(k) Volume Flow Rate (by iterative method).

$$D = T = \rho_{w} Q \left(\int_{1}^{2g C_{2} Q^{2} + V^{2}} - V \right)$$

(1) Velocity Ratio:

$$k = \frac{D}{\rho_w Q V}$$

(m) Pump Head:

$$H_p = C_2 Q^2$$

(n) Exit Velocity:

$$V_i = (k+1) V$$

(o) Nozzle Exit Area:

$$A_{j} = Q \sqrt{\frac{1 + K_{D}}{2g c_{2} Q^{2} + V^{2}}}$$

(P) Total Loss Coefficient:

$$K_{L} = \left[1 - \frac{1}{(1+k)^{2}}\right] \frac{1-\eta_{e}}{\eta_{e}} + \frac{K_{D}}{\eta_{e}}$$

(q) Propulsive Efficiency:

$$\eta_{p} = \frac{2k}{(1+k)^{2}(1+K_{L})-1}$$

(r) A suitable indication of the onset of cavitation may be the ratio of the pump inlet static head to the pump head rise:

$$G = \frac{H_{spi}}{H_{p}} = \frac{H_{atm} - H_{V} - H_{D} + H_{dyn} - \frac{Q^{2}}{2g A_{p}^{2}}}{H_{p}}$$

or

$$\frac{32.51 - \frac{{}^{2}_{D} v_{j}^{2}}{2g} + \frac{v^{2}}{2g} - \frac{Q^{2}}{2g A_{p}^{2}}}{c_{2} Q^{2}}$$

The minimum noncavitating values of σ for specified operating conditions and duct-pump combinations have not been ascertained fully.

DISCUSSION

Table 1 shows the variation of the main design parameters evaluated by the program. Four gross weights and three length-to-beam ratios were selected as inputs. The values of ℓ /b were 2.0, 7.0, and 3.74 (which represents the geometric mean between 2.0 and 0). The selection of design speeds and wave heights was arbitrary; however, the propulsive efficiency was insensitive to relatively large variations of these two parameters so that little benefit was realized by optimization.

Both the weight-to-horsepower ratios (W/ $\mathbb P$) and the specific power P_R/WV have been presented as performance figures of merit. From the standpoint of conventional power, the parameter P_R/WV affords a satisfactory prediction of the range-speed-payload capabilities of the vehicle. However, when nuclear power is considered, the principal consideration becomes the allowable weight per horsepower of the propulsion machinery, which must be a reasonable fraction of the total vehicle weight per horsepower. In the graphs of $W/\mathbb P$ versus V_k , $W/\mathbb P$ may be considered as an "equivalent" L/D ratio when plotted for a single velocity.

A study of the graphical data revealed sever 1 interesting trends in W/ \mathbb{P} as a function of the primary design parameters (weight, length-to-beam ratio, and specific cushion loading, w/ \mathbb{P}). In general, a combination of these parameters exists that will maximize W/ \mathbb{P} for a given operating mode of velocity and sea state. However, due to the complexities and interactions involved in this type of analysis, it is difficult to make any simple statements on formulations with regard to optimizing performance. Rather, the procedure used here will be to illustrate graphically the optimizing trends attributed to variations of the design parameters and to indicate limiting factors in these trends.

Figure 3 is a summary plot computed from six different £/b designs of a 20,000-ton vessel operating in ten-foot waves. It should be noted that the data for this particular vessel were computed using conventional

water propellers and not water jets. A value of $w/\sqrt{s}=1.1$ was selected, based on structural considerations. Figure 4 shows the influence of varying the specific loading w/\sqrt{s} . For a speed of 50 knots at $w/\sqrt{s}=0.5$, the ℓ/b for best W/P is approximately 5 and, at $w/\sqrt{s}=2.1$, the optimum ℓ/b value from a W/P standpoint is 9.0. It may be noted that the peak value of the $w/\sqrt{s}=1.1$ curve corresponds with the value of W/P at 50 knots shown in Figure 3.

Referring again to Figure 3, it is evident that at the higher speeds the lower ℓ/b provides better performance, and the drag hump is present only at the lower ℓ/b . These phenomena are attributable directly to the nature of the wavemaking drag, as shown in Figure 1. The total drag curve (D/W) at high L/b increases rapidly with velocity. As the percentage contribution of wavemaking drag is sharply reduced with increasing ℓ/b , the sidewall hydrodynamic drag begins to dominate, because of the greatly increased bubble length. The low ℓ /b advantage of super-hump operation is therefore eliminated and sub-hump operation now becomes attractive. At 1/b values above 7.0, the sideboard drag exceeds 80 percent of the total drag. The tradeoff beyond this point is straightforward. An increase of L/b produces a decrease of the wave drag component and a corresponding increase of sidewall drag so that no net drag reduction is possible. Another drag tradeoff is evident in Figure 4. As w/\sqrt{s} increases, at any given ℓ/b , the wavemaking drag increases $\left(D_{W}/W \text{ and } D_{s,b}/W\right)$ and the sidewall hydrodynamic drag $D_{s,a}/W$ is reduced. The intersection of these drag curves represents a minimum value of total drag and an optimum of w/\sqrt{S} . This relationship is evident in Figure 4 at an L/b of 9.0 where $w/\sqrt{s} = 0.5$ represents a pre-minimum value; but, at a value of 1.1, the D/W ratio is optimized. The effect of weight variation is illustrated in Figure 5.

The primary intent of this paper has been to indicate tradeoffs in performance obtainable by varying the primary design parameters. However, much additional information may be derived by studying and cross-plotting the data. In particular, the variation of the cavitation index σ with L/b,

weight, w/ \sqrt{s} , wave height, and K_D is presented. Before additional refinements are added to the CAB design, the seriousness of the cavitation problem should be ascertained and modifications of K_D, pump geometry, etc. should be determined.

Multiple graphs (Figure 6 through Figure 17) have been prepared for all the data. By interpolation of these graphs, the CA3 performance can be estimated. If precise information on a specific design is desired, however, a detailed computer analysis would be required.

Aerodynamics Laboratory David Taylor Model Basin Washington, D. C. 70007 January 1967

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Table 1 Variation of GAB Input Parameters

Figure	89 99 99 99	78 76 76	88 8 8 8 9 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	96 96 96	10a 10b 10c 10d	1116 1116 1116
A (ft ²)	2.123 1.992 2.333 2.190	2.460 2.470 2.705 2.715	0.7910 0.7494 0.8694 0.8237	38.12 34.96 41.90 38.43	30.36 33.83 33.37 30.78	10.78 11.96 11.95 13.15
25	1.042 × 10 ⁻³ 1.174 × 10 ⁻³ 2.108 × 10 ⁻³ 2.377 × 10 ⁻³	7.572 × 10 ⁻⁴ 8.021 × 10 ⁻⁴ 1.533 × 10 ⁻³ 1.623 ∨ 10 ⁻³	1.268 × 10 ⁻⁴ 1.225 × 10 ⁻⁴ 2.566 × 10 ⁻⁴ 2.479 × 10 ⁻⁴	4.016 × 10 ⁻⁶ 4.675 × 10 ⁻⁶ 8.130 × 10 ⁻⁵ 9.462 × 10 ⁻⁵	5.659 × 10 ⁻⁶ 5.817 × 10 ⁻⁶ 1.145 × 10 ⁻⁴ 1.177 × 19 ⁻⁴	8.986 × 10 ⁻⁶ 8.300 × 10 ⁻⁶ 1.819 × 10 ⁻⁶ 1.680 × 10 ⁻⁵
7	83.203 71.965 83.203 71.965	113.8 98.41 113.8 98.41	155.7 134.6 155.7 134.6	179.3 155.0 179.3 155.0	245.1 212.0 245.1 212.0	335.4 290.1 335.4 290.1
y _o	0.763	0.763	0.763	1.644	1.644	1.644
c_1^1	1.133	1.133	1.133	1.133	1.133	1.133
္မ	0.100	0.053	0.029	0.100	0.053	0.029
$_{\Gamma}^{\Gamma}$	0.200	0.200	0.200	0.200	0.200	0.200
H Design (ft)	1.00	7.00	4.00	7.00	4.00	10.00
V _k Design	83.19 83.10 83.14 83.10	82.87 83.78 82.87 83.78	42.14 41.16 42.19 41.16	126.6 126.2 126.6 126.6	124.3 125.4 124.3 125.4	64.95 66.16 64.95 66.16
⁷ D	0.04	0.04	0.04	0.04	0.0%	0.0%
,e"	0.08	0.08	0.08	0.08	0.08	0.08
{:/^/A	1.1 1.7 1.1 1.1	1.1	1.1 1.7 1.1 1.1	1.1	1.1	1.1 1.7 1.1 1.1
u/b	2.00	3.74	7.00	2.00	3.74	7.00
f fn tons	100	100	100	1000	1000	1000 i

Table 1 (Concluded)

Pigure	12a 12b 12c 12d	13a 13b 13c 13d	14a 14b 14c 14d	15a 15b 15c 15c	16a 16b 16c 16d	178 17b 17c 17d
A _p (ft ²)	377.1 364.8 414.5 401.0	436.4 430.8 479.7 473.5	106.0 123.0 116.5 135.3	2452 2817 2695 3097	2424 2848 2665 3131	988.2 1071 1086 1178
c ₂	2.079 × 10 ⁻⁶ 2.282 × 10 ⁻⁶ 4.208 × 10 ⁻⁶ 4 3 × 1 ⁻⁶	1.599 × 10 ⁻⁶ 3.251 × 10 ⁻⁶ 3.236 × 10 ⁻⁶	7.564 × 10 ⁻⁶ 6.003 × 10 ⁻⁸ 1.430 × 10 ⁻⁷ 1.215 × 10 ⁻⁷	4.863 × 10 ⁻⁸ 3.959 × 10 ⁻⁸ 9.843 × 10 ⁻⁵ 8.013 × 10 ⁻⁸	4.899 × 10 ⁻⁸ 3.426 × 10 ⁻⁸ 9.915 × 10 ⁻⁶ 6.934 × 10 ⁻⁸	5.970 × 10 ⁻⁸ 4.470 × 10 ⁻⁸ 1.208 × 10 ⁻⁸ 9.049 × 10 ⁻⁸
¥	386.2 334.0 386.2 334.0	528.1 456.8 528.1 456.8	722.5 624.9 722.5 624.9	832.0 719.6 832.0 719.6	1137.8 984.1 1137.8 984.1	1556.6 1346.3 1556.6 1346.3
°c,	3.541	3.541	3.541	7.628	7.628	7.628
c_1	1.133	1.133	1.133	1.133	1.133	1.133
° c	0.100	0.053	0.029	0,100	0.053	0.029
cr	0.200	0.200	0.200	0.200	0.200	0.200
H Design (ft)	7.00	7.00	10.00	7.00	7.00	10.00
V _k Design	166.0 166.7 166.0 166.7	166.9 166.1 166.9 166.9	90.80 92.89 90.80 92.89	165.6 167.6 165.6 167.6	165.2 164.2 165.2 164.2	126.6 123.9 126.6 123.9
Ž ^c	0.04	0.08	0.08	0.04	90°0	0.04
يم	0.08	0.08	0.08	0.16	0.08	0.08
x /3	1.1	1.1	1.7			11.1
q,/7	2.00	3.74	7.00	2.00	3.74	7.00
W 1n tons	10,000	10,000	10,000	100,660	100,000	100,000

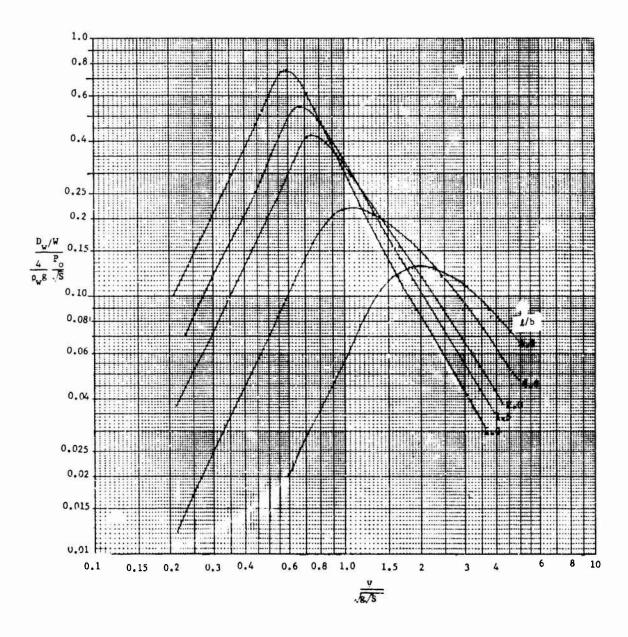


Figure 1 - Wavemaking Drag of Rectangular Planform

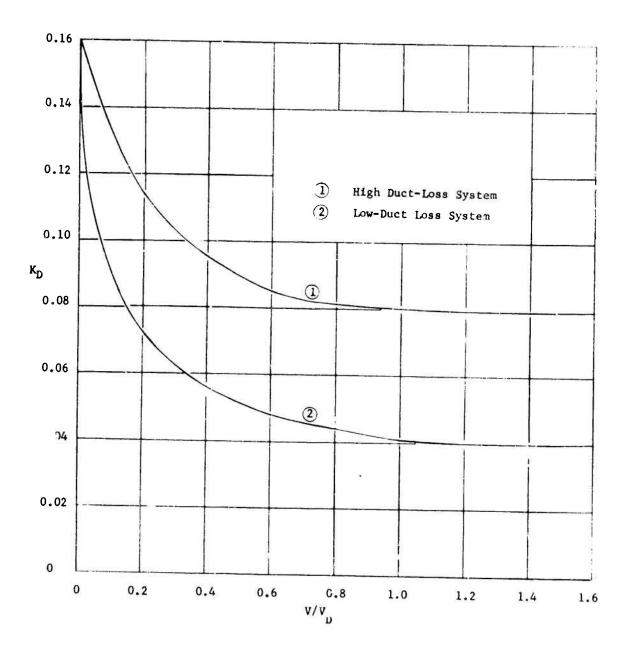


Figure 2 - Assumed Parabolic Variations of Duct Loss Coefficient, K_{D}

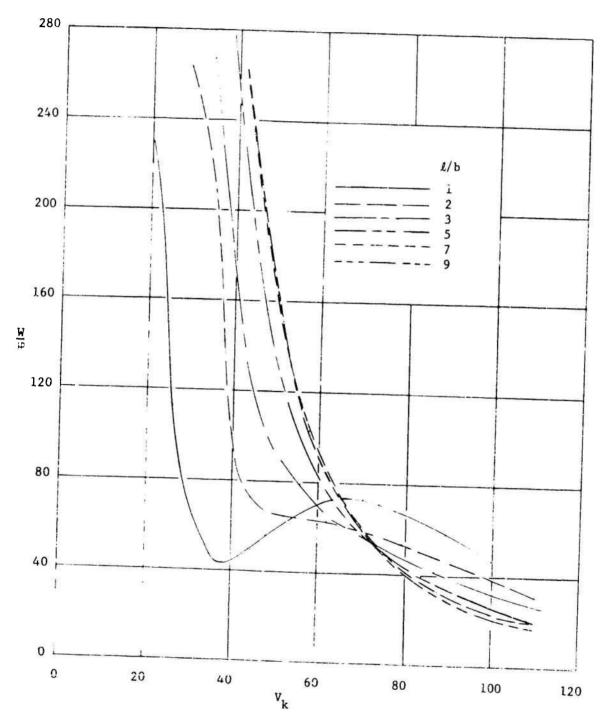


Figure 3 - Effect of Length-to-Leam Ratio on CAB Performance W = 20,000 Tons; H = 10 Feet; $w/\sqrt{S} = 1.1$ $1b/ft^3$

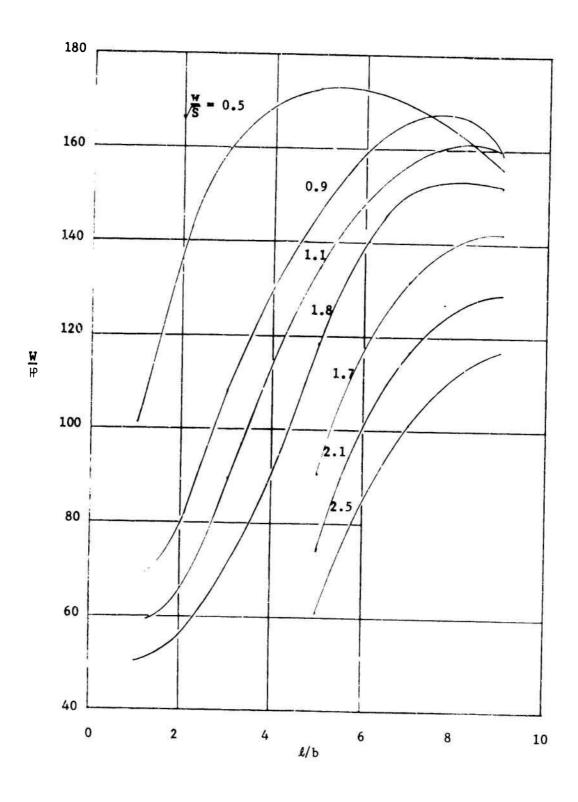


Figure 4 - Effect of Specific Cushion Loading on CAB Performance W = 20,000 Tons; $V_k = 50$ Knots; H = 10 Feet

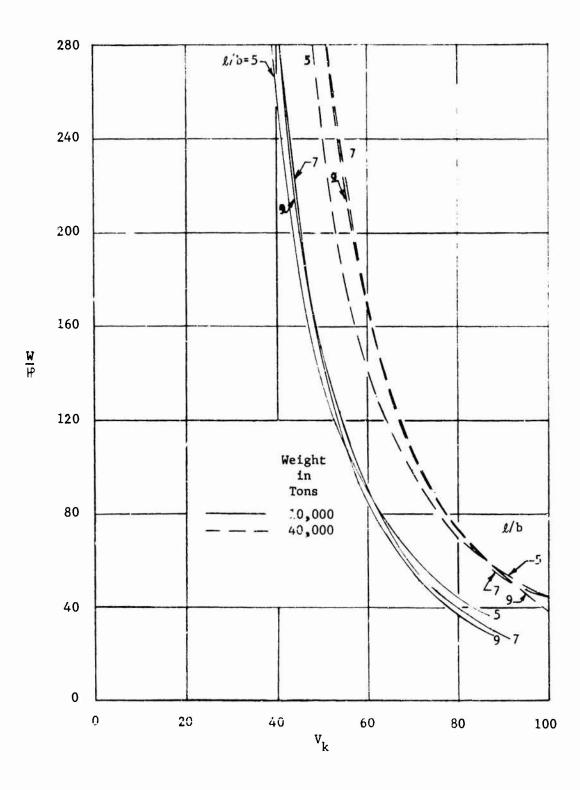
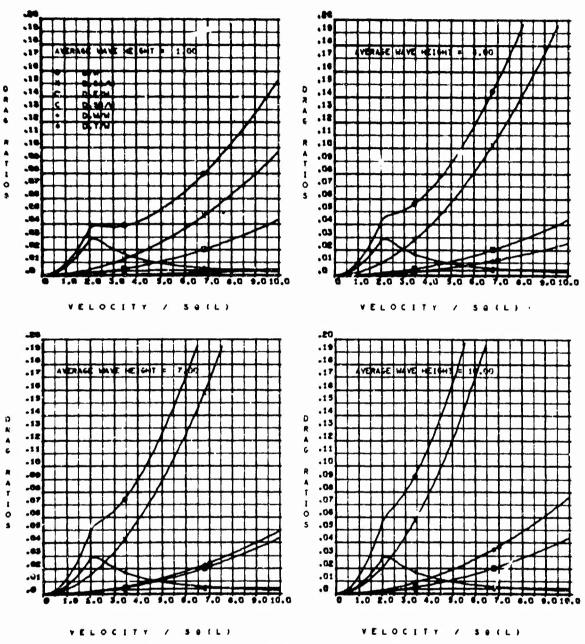


Figure 5 - Effect of Weight Variation on CAB Performance H = 10 Feet; w/\sqrt{s} = 1.1 lb/ft^3



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 6 - General Performance Parameters of 100 Ton CAB with $\ell/b = 2.0$ (a) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

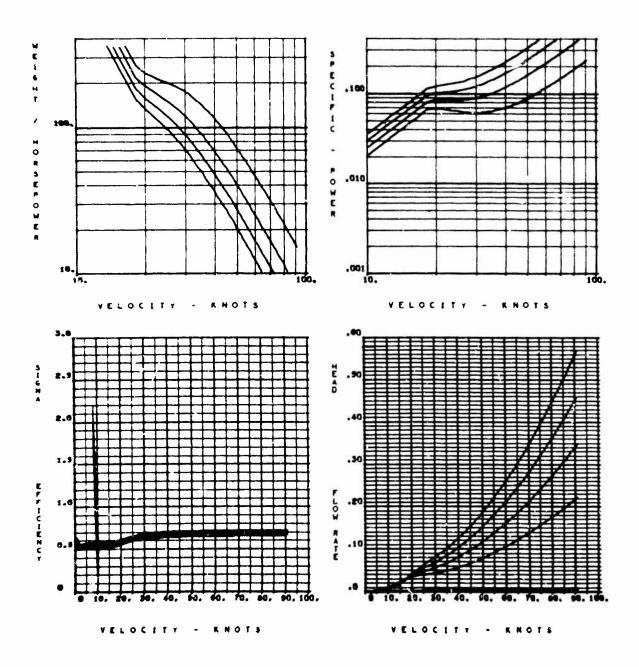
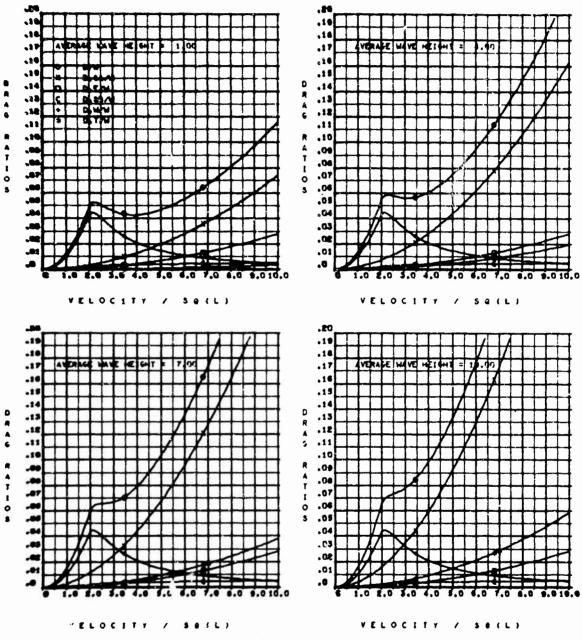


Figure 6 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 6 (Continued) (b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

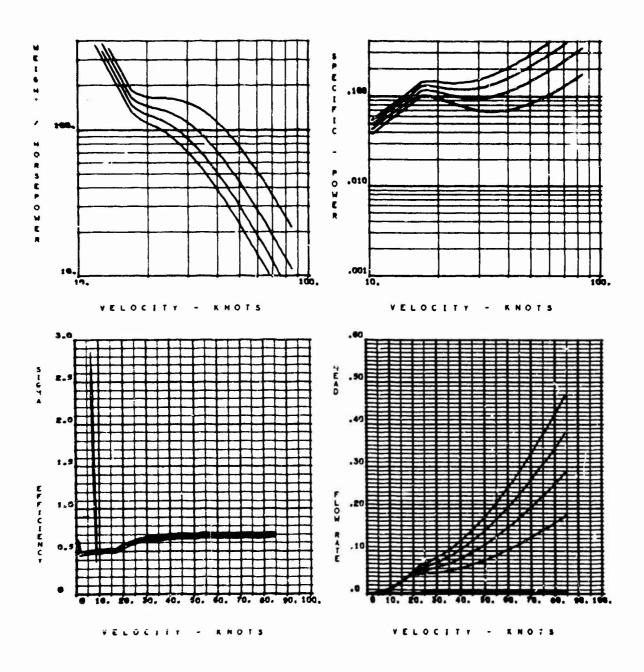
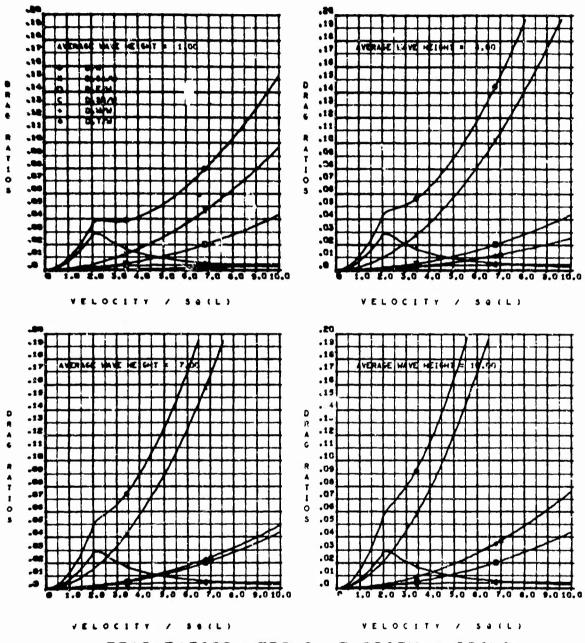


Figure 6 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 6 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.1$

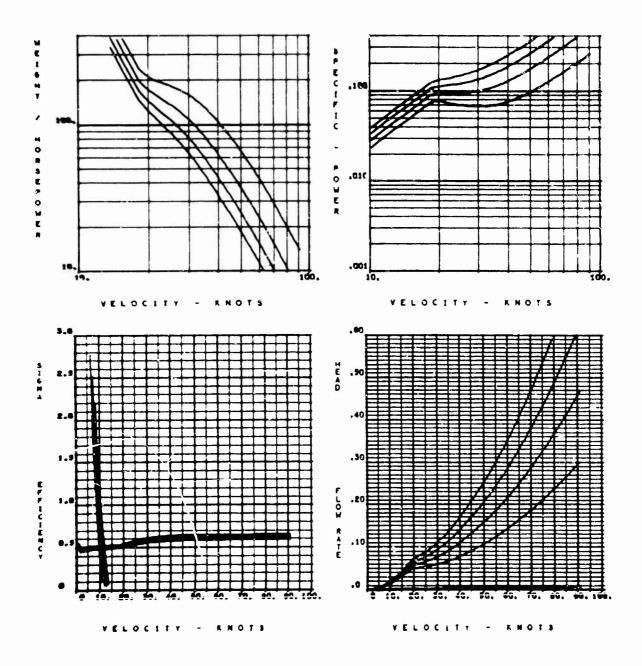
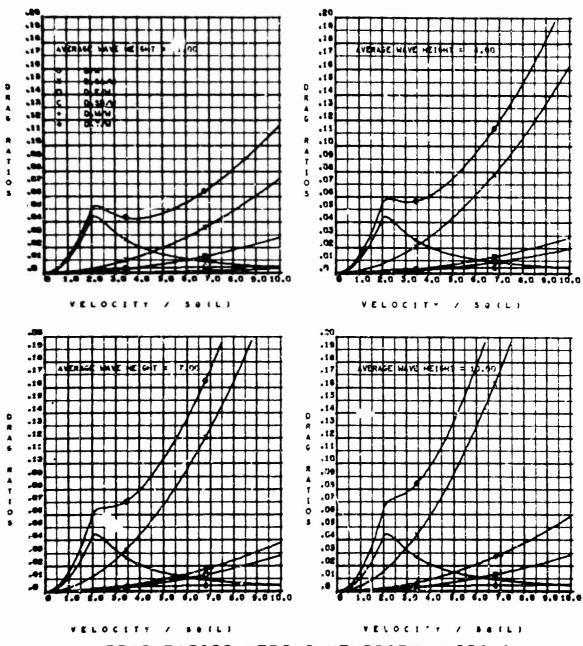


Figure 6 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 6 (Continued)
(d) $K_{D_{D}} = 0.08$, $K_{D_{S}} = 0.16$, $w/\sqrt{s} = 1.7$

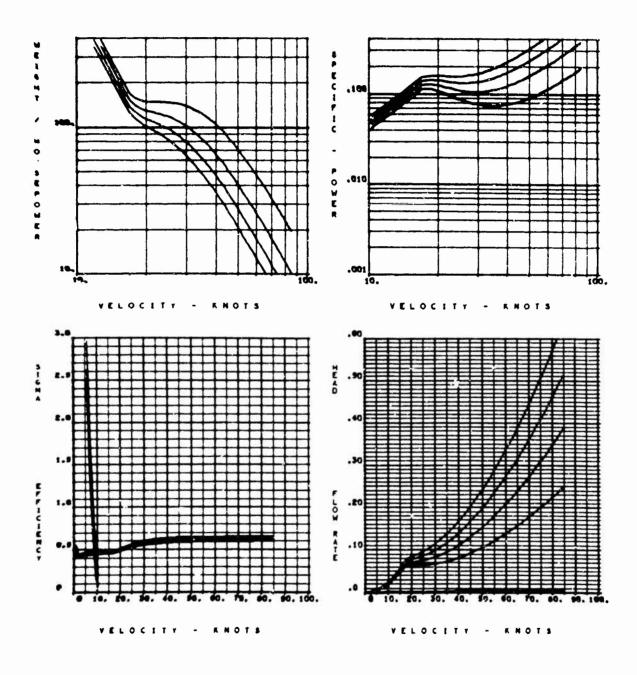
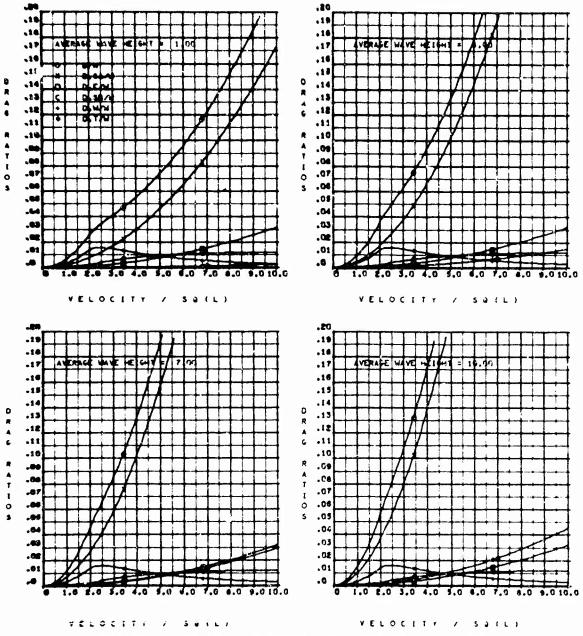


Figure 6 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 7 - General Performance Parameters of 100 Ton CAB With $\ell/b=3.74$ (a) $K_{D_D}=0.04$, $K_{D_S}=0.08$, w/, S=1.1

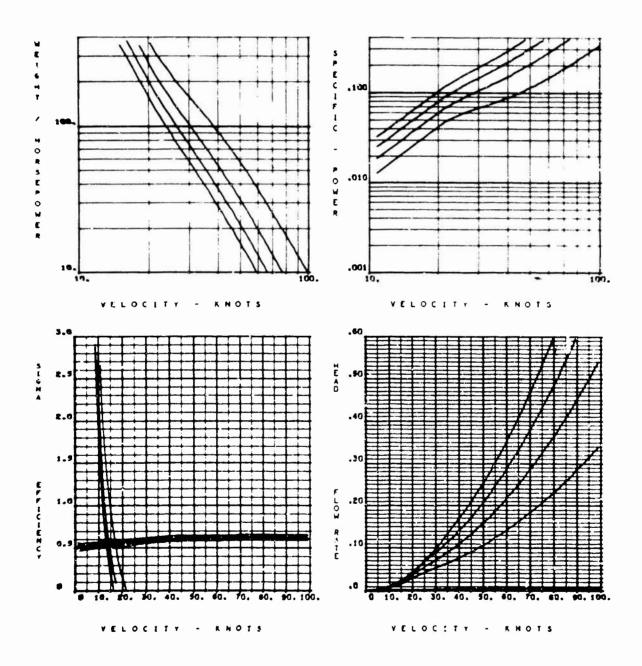
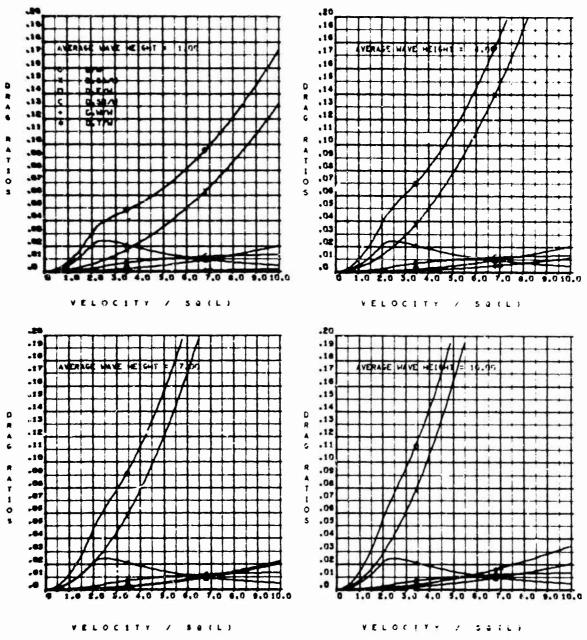


Figure 7 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 7 (Continued)
(b)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w/s = 1.7$

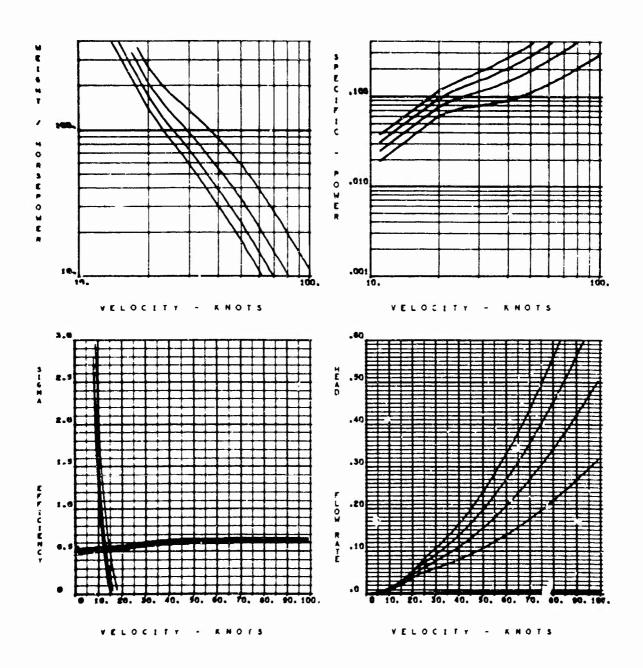
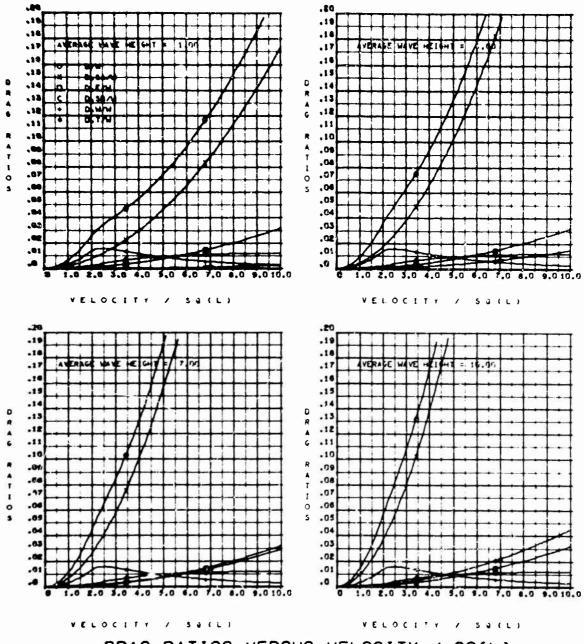


Figure 7 (Continued)

(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 7 (Continued)
(c)
$$K_{D_{\overline{D}}} = 0.08$$
, $K_{D_{\overline{S}}} = 0.16$, $w//\overline{S} = 1.1$

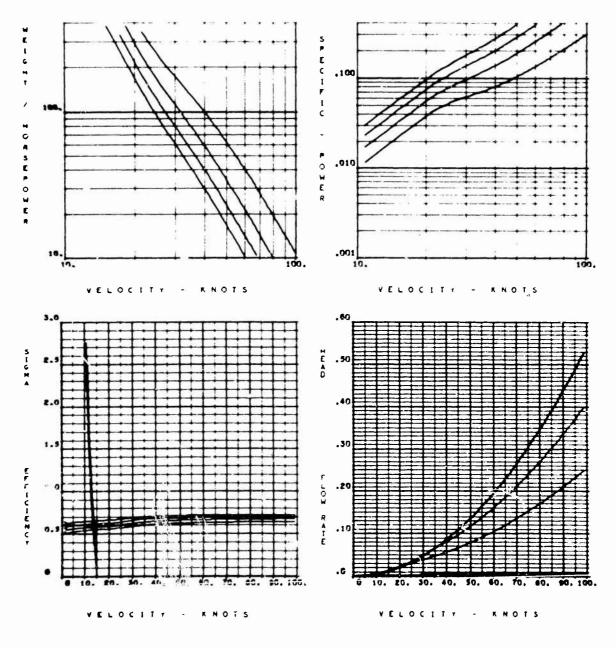
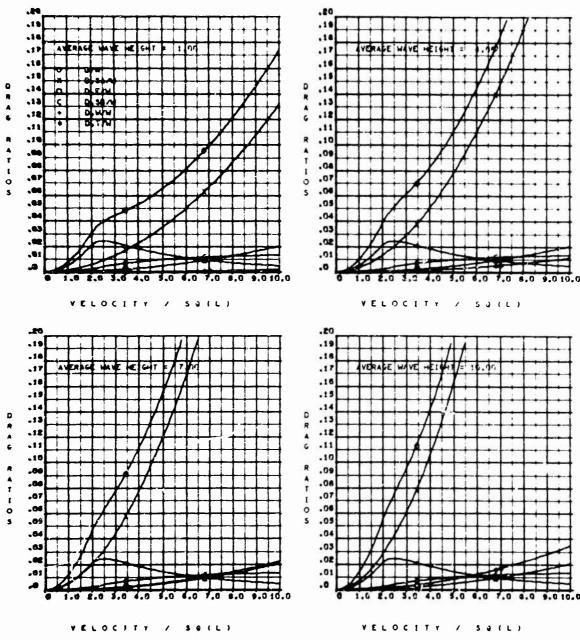


Figure 7 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 7 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

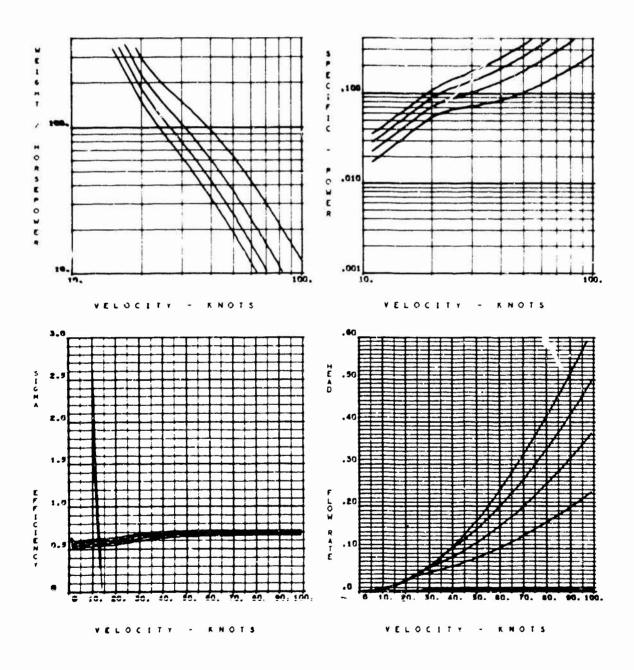
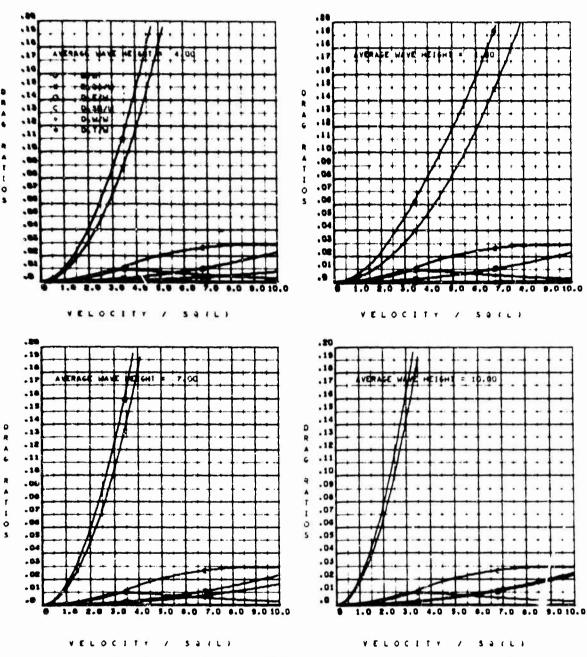


Figure 7 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 8 - General Performance Parameters of 1.00 Ton GAB With ℓ/b = 7.0

(a)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w//S = 1.1$

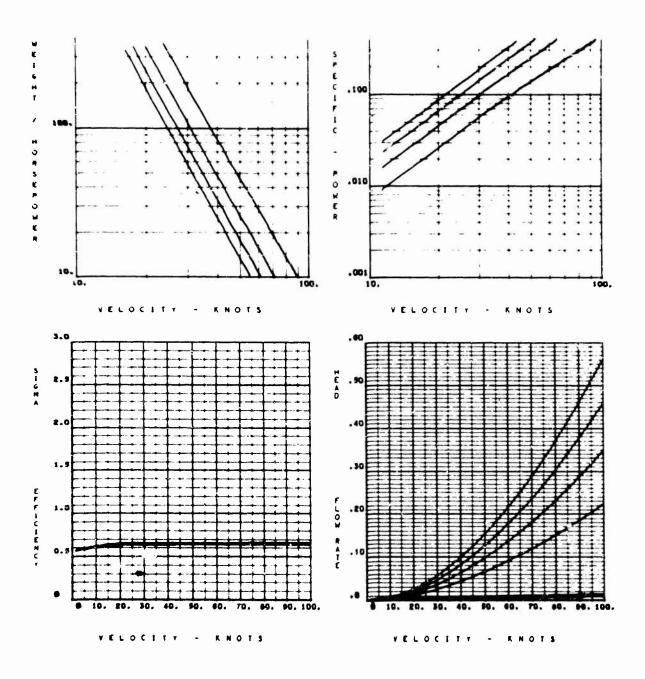
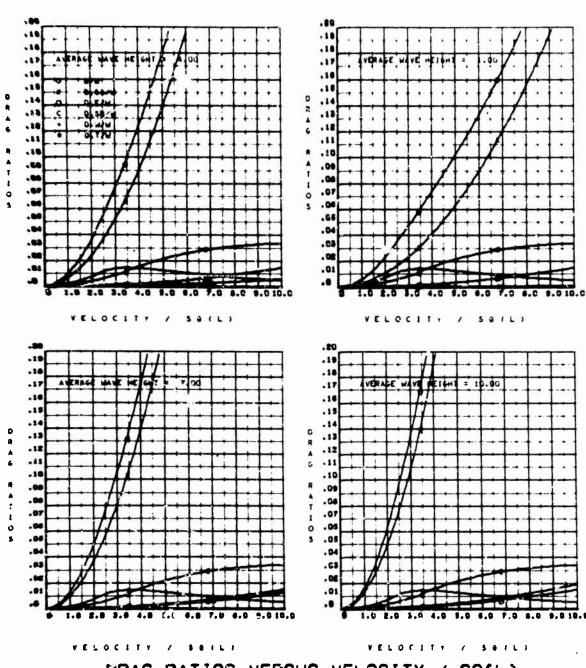


Figure 8 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 8 (Contin: d) (b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

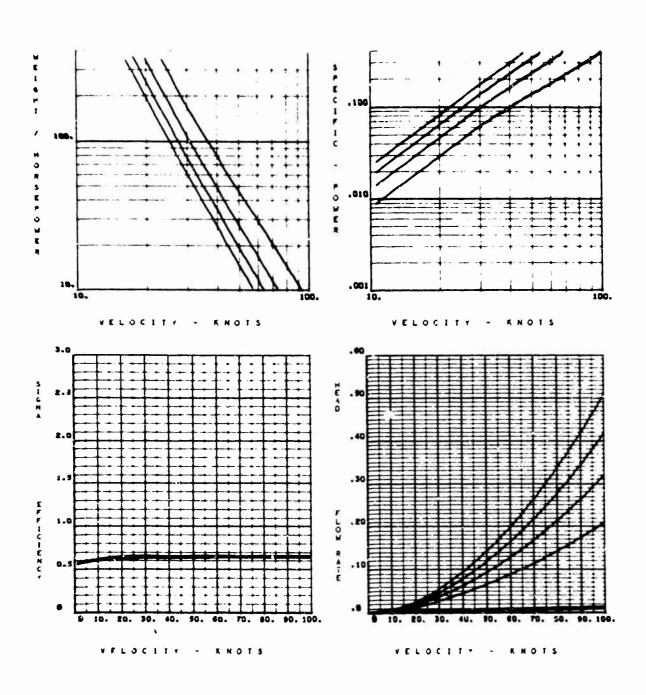
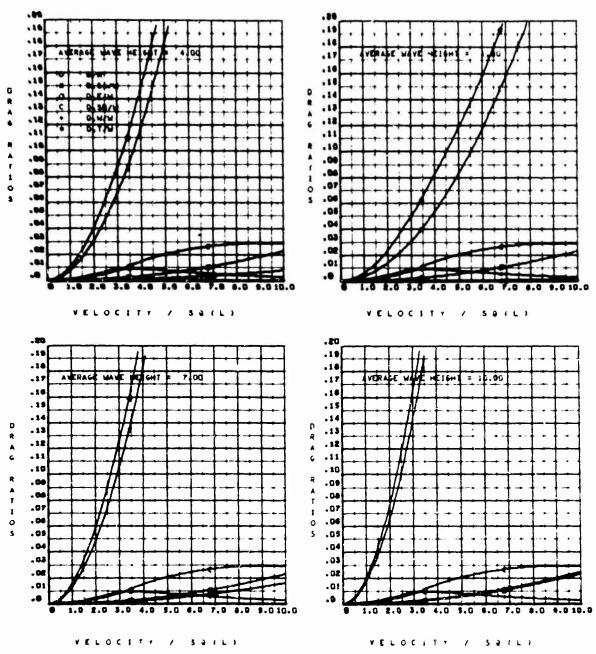


Figure 8 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

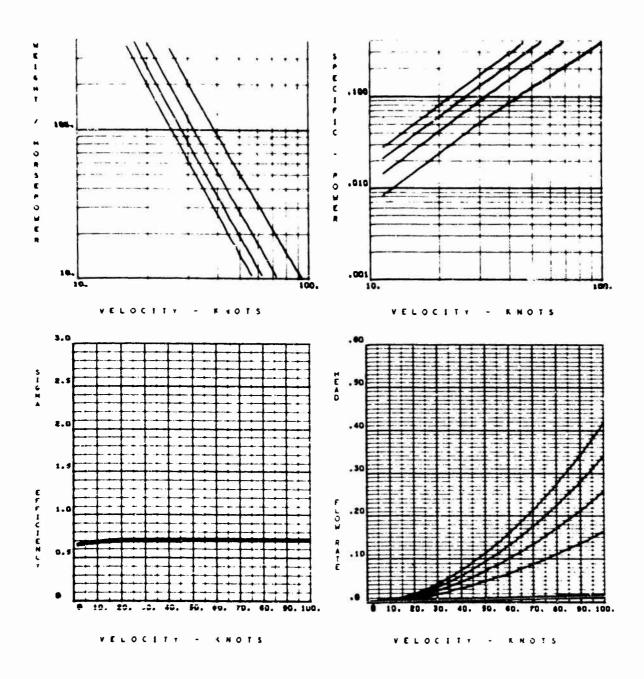
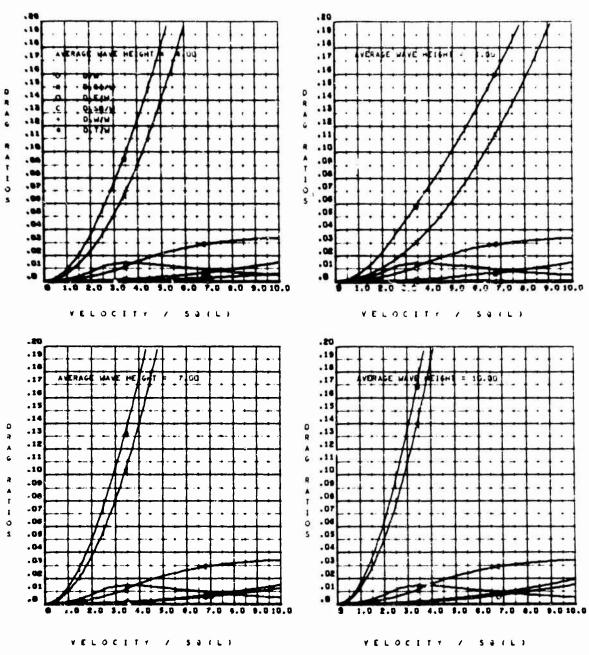


Figure 8 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 8 (Continued)
(d)
$$K_{D_D} = 0.08$$
, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

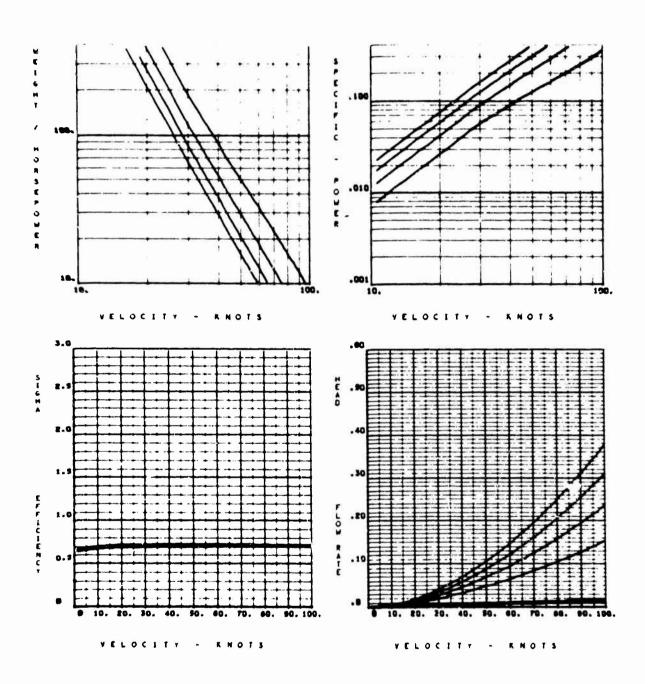
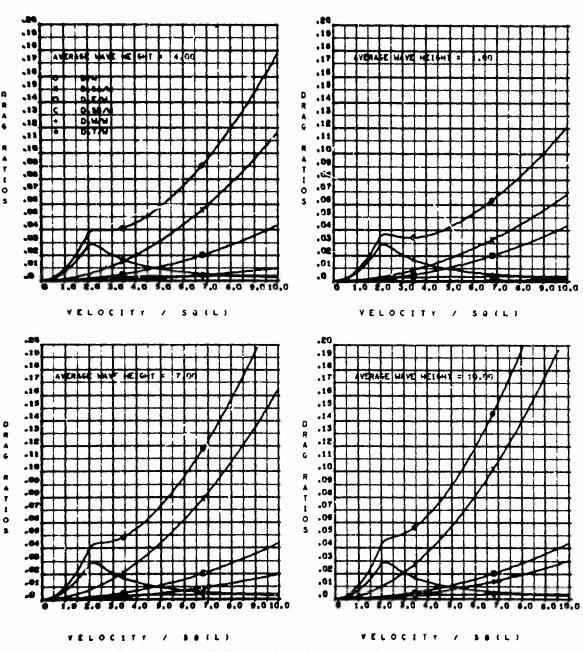


Figure 8 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 9 - General Performance Parameters of 1000 Ton CAB With ℓ/b = 2.0 (a) K_{D_D} = 0.04, K_{D_S} = 0.08, w/\sqrt{s} = 1.1

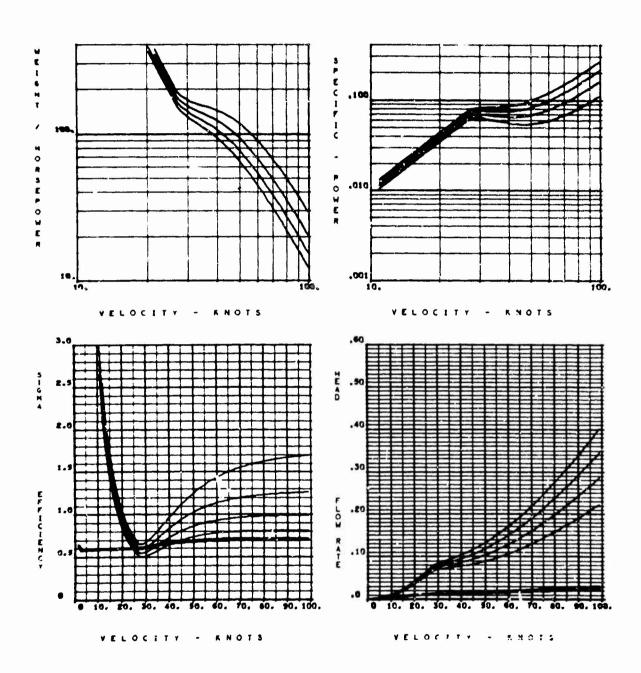
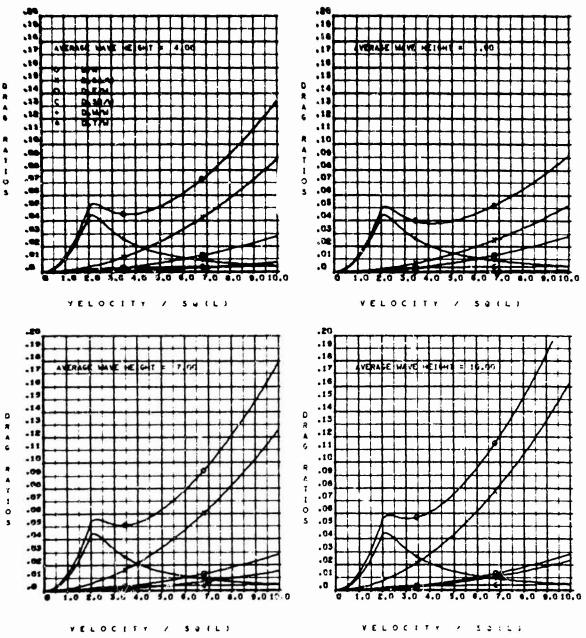


Figure 9 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 9 (Continued)
(b) $K_{D_D} = 0.94$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

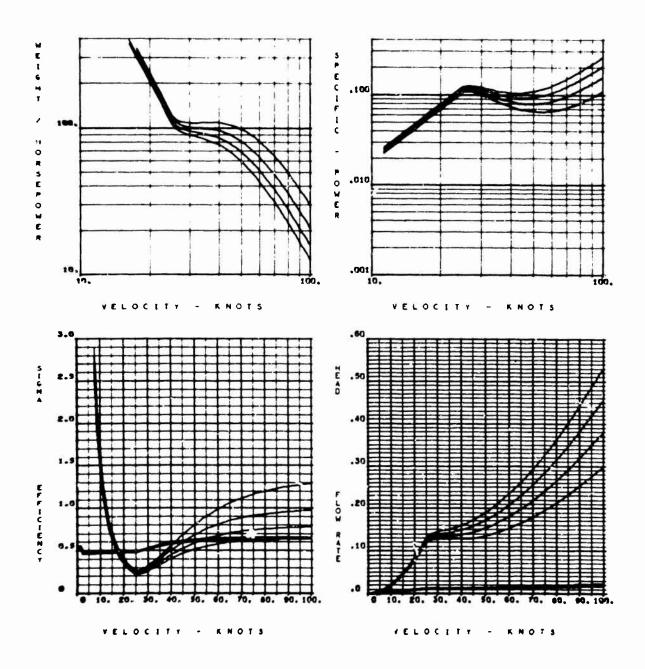
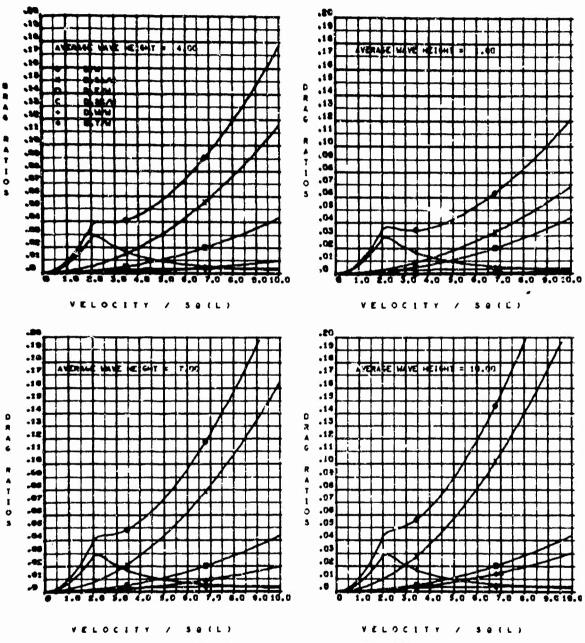


Figure 9 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 9 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.1$

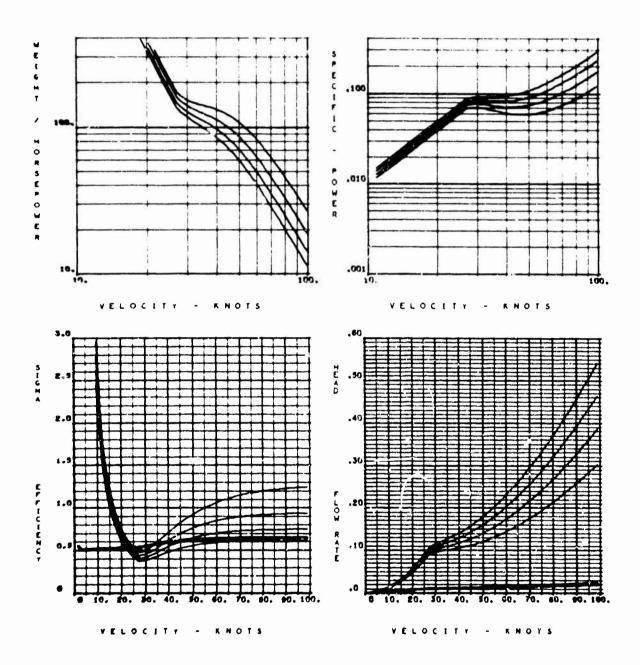
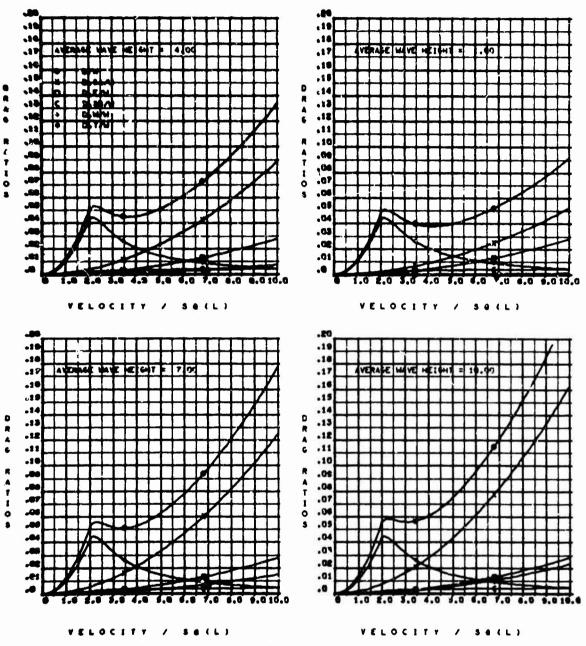


Figure 9 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 9 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

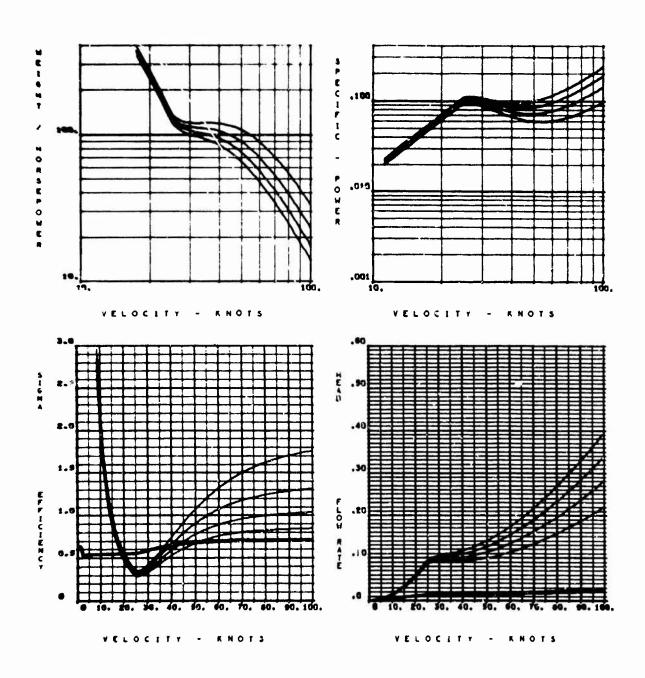
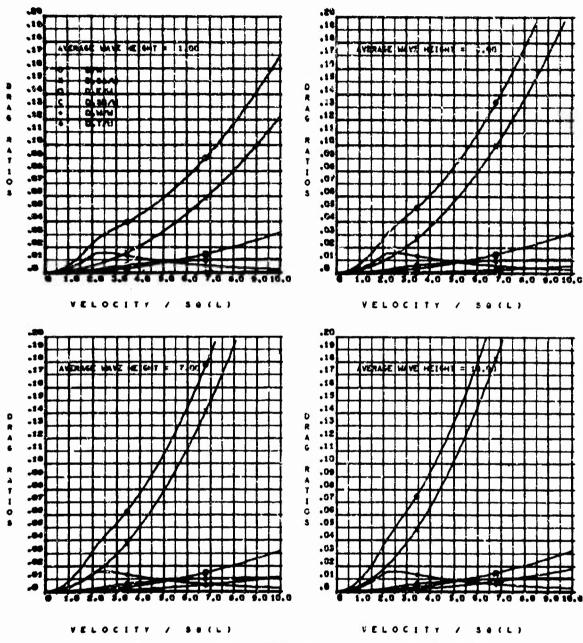


Figure 9 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 10 - General Performance Parameters of 1000 Ton CAB With $\ell/b = 3.74$

(a)
$$K_{D_{ij}} = 0.04$$
, $K_{D_{g}} = 0.08$, $w/\sqrt{s} = 1.1$

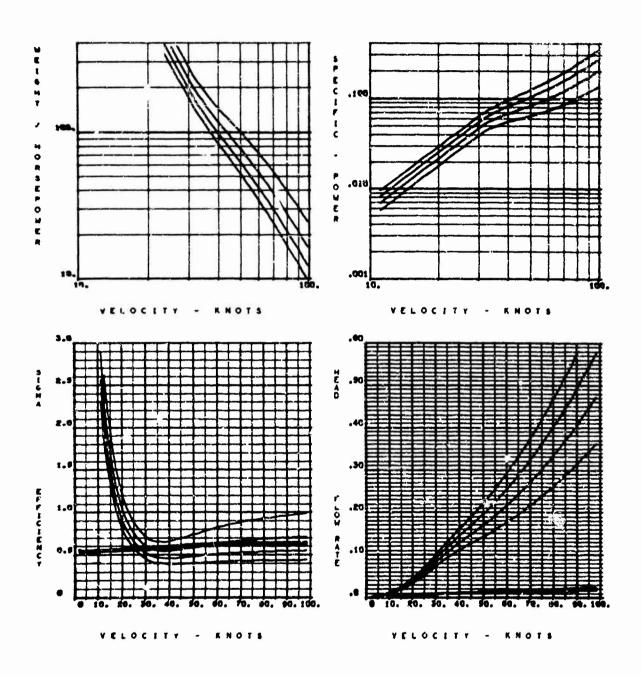
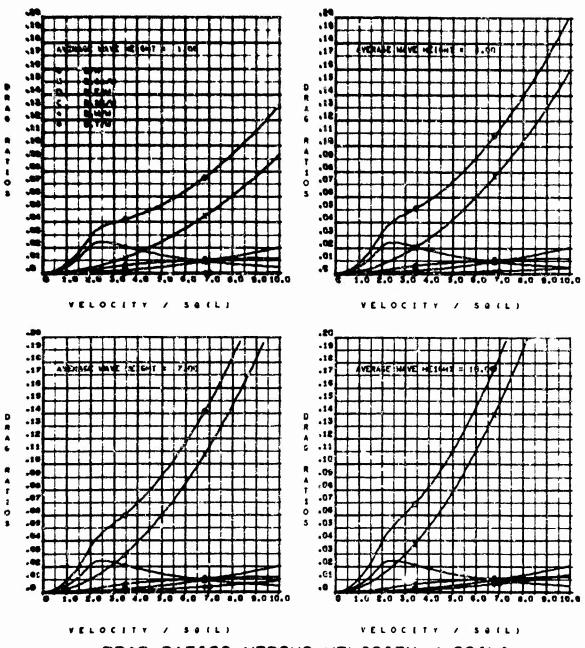


Figure 10 (Continued)

(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 10 (Continued)
(b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

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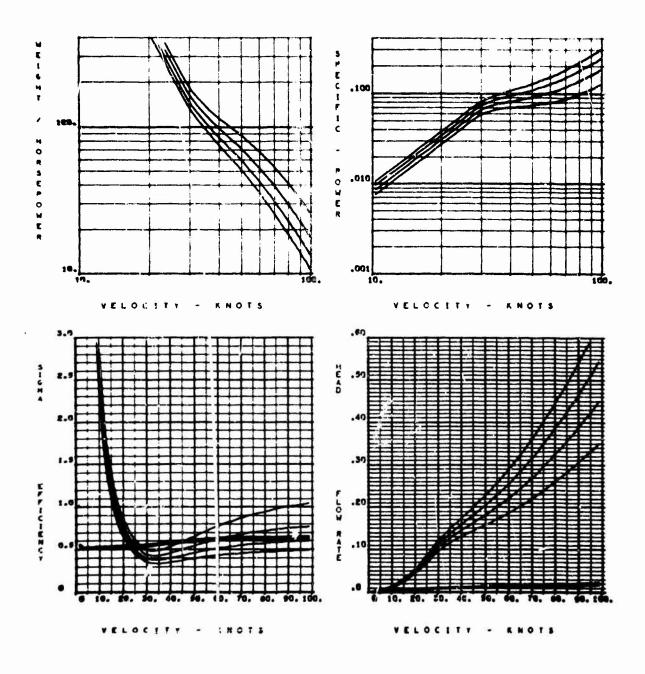
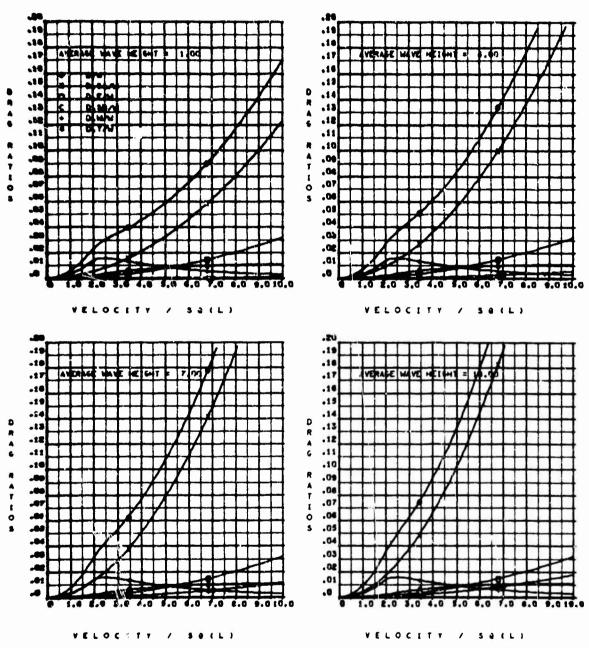


Figure 10 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 10 (Continued) (c) $K_{D_{S}} = 0.08$, $K_{D_{S}} = 0.16$, $w/\sqrt{S} = 1.1$

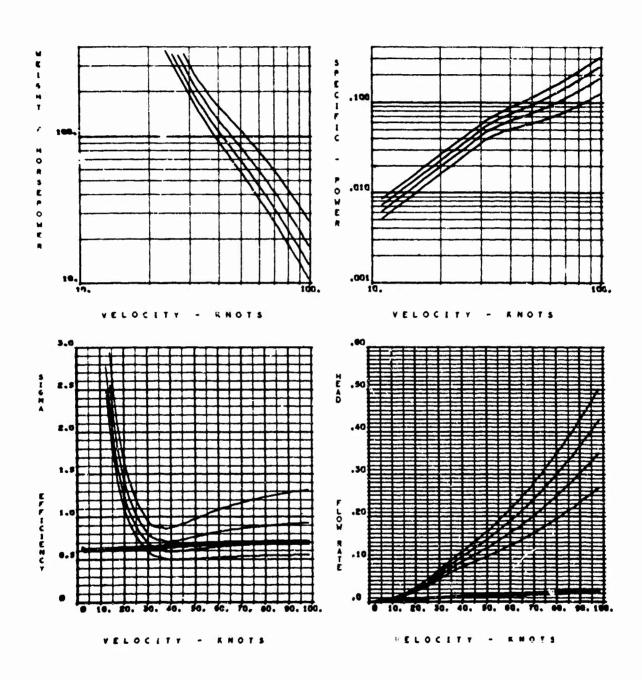
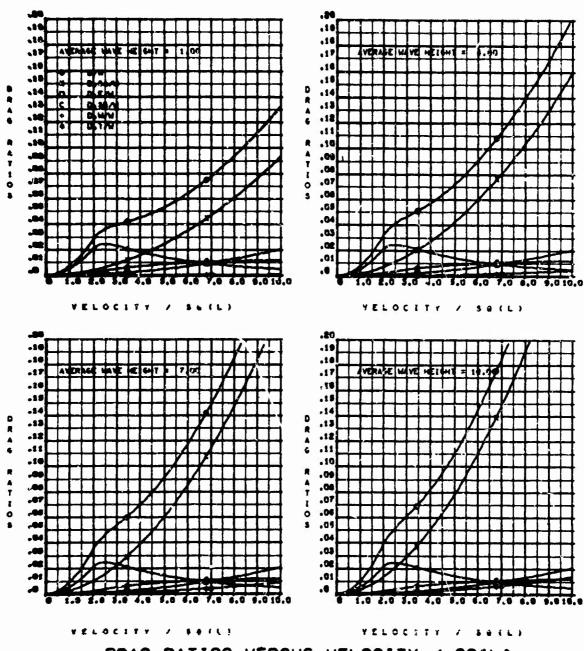


Figure 10 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 10 (Continued) (d) $K_{D_D} = 0.08$, $K_{D_g} = 0.16$, $w/\sqrt{s} = 1.7$

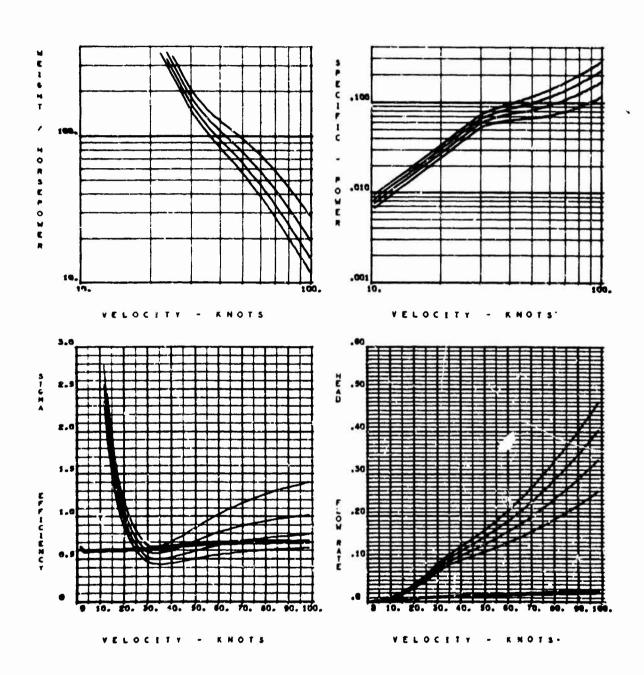
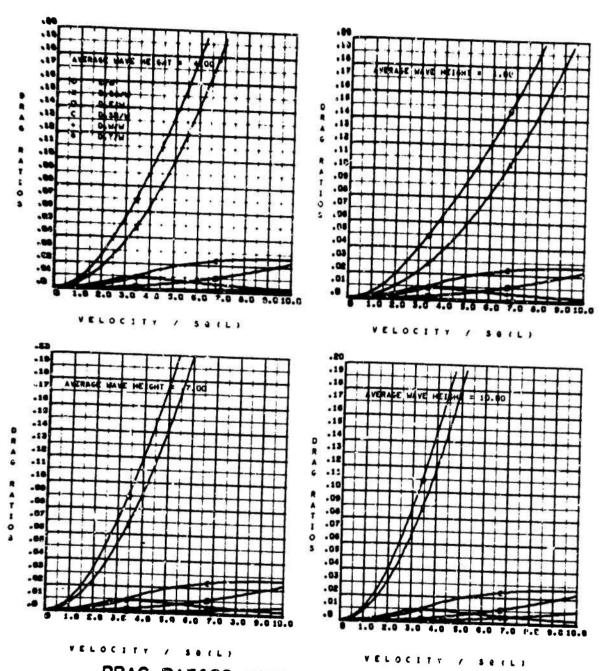


Figure 10 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 11 - General Performance Parameters of 1000 Ton CAB With $\ell/b = 7.0$ (a) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

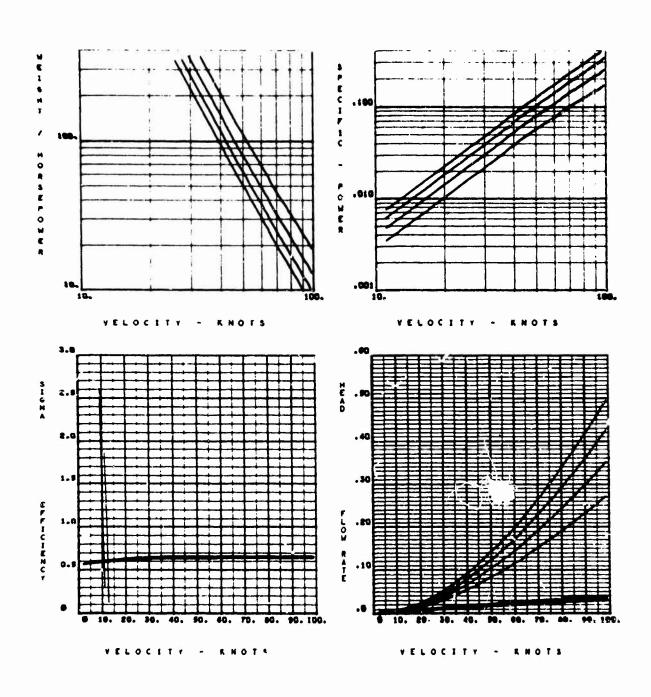
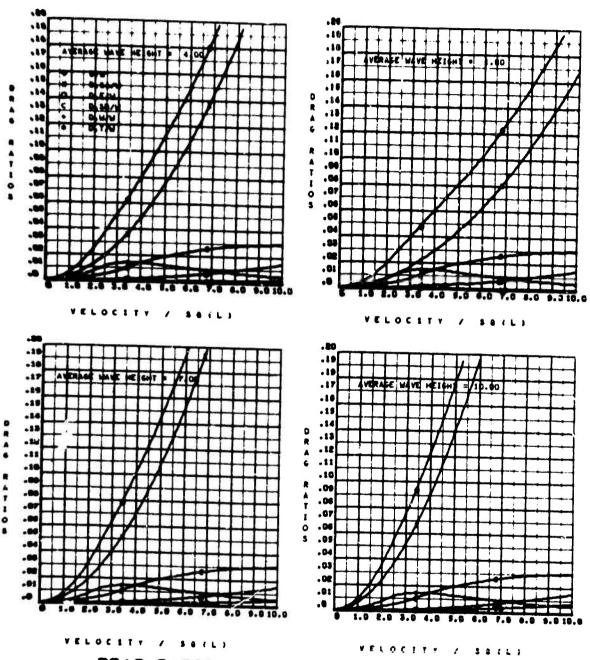


Figure 11 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 11 (Continued)
(b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

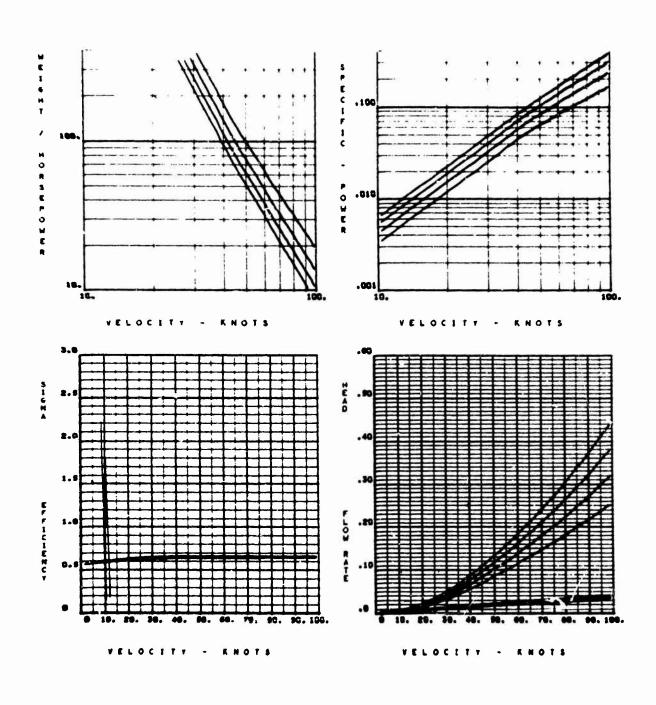
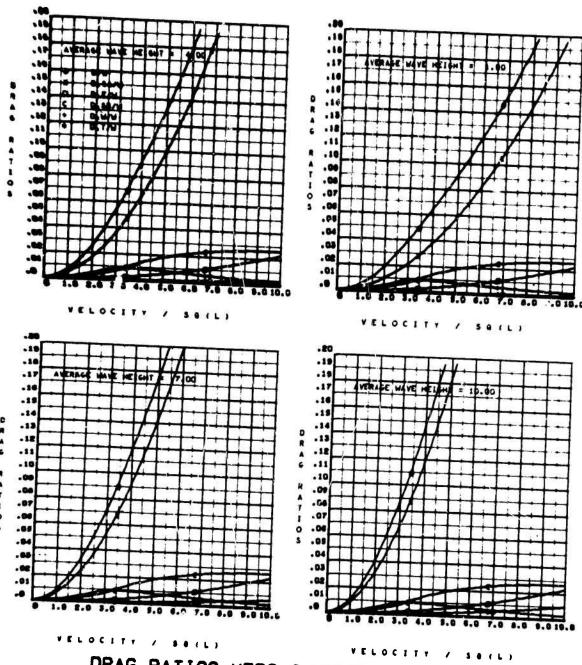


Figure 11 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 11 (Continued)
(c) $K_{D_{D}} = 0.08$, $K_{D_{S}} = 0.16$, $w/\sqrt{S} = 1.1$

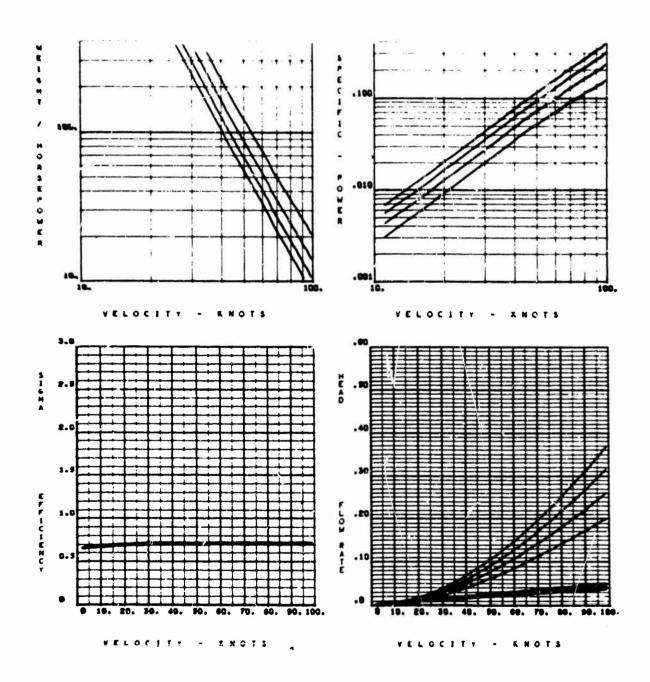
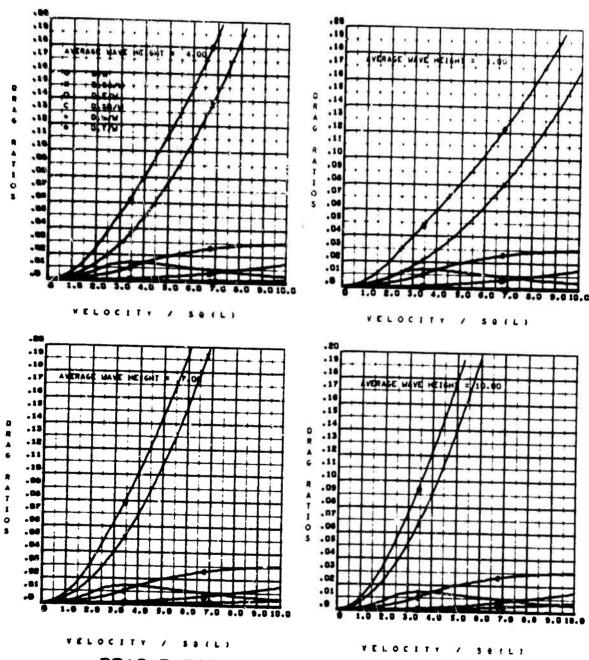


Figure 11 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 11 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{\varepsilon} = 1.7$

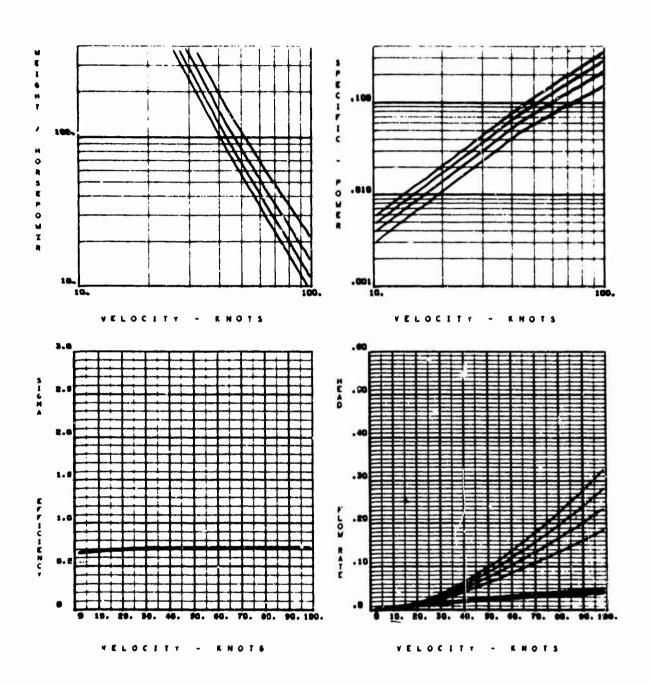
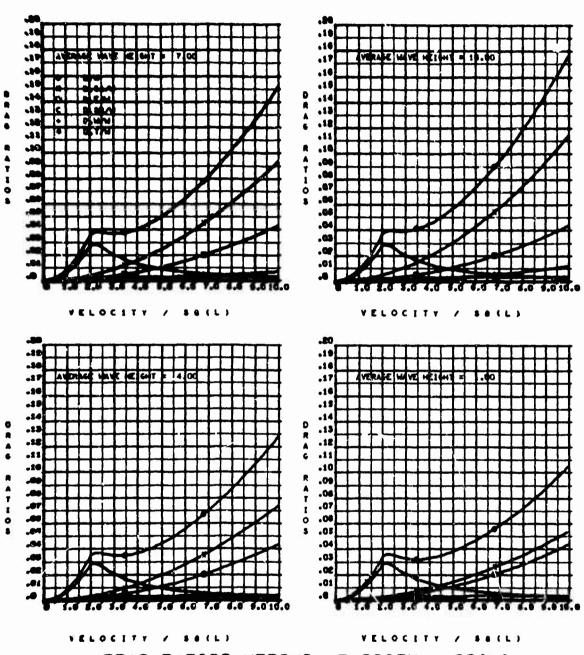


Figure 11 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 12 - General Performance Parameters of 10,000 Ton CAB With t/b = 2.0(a) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

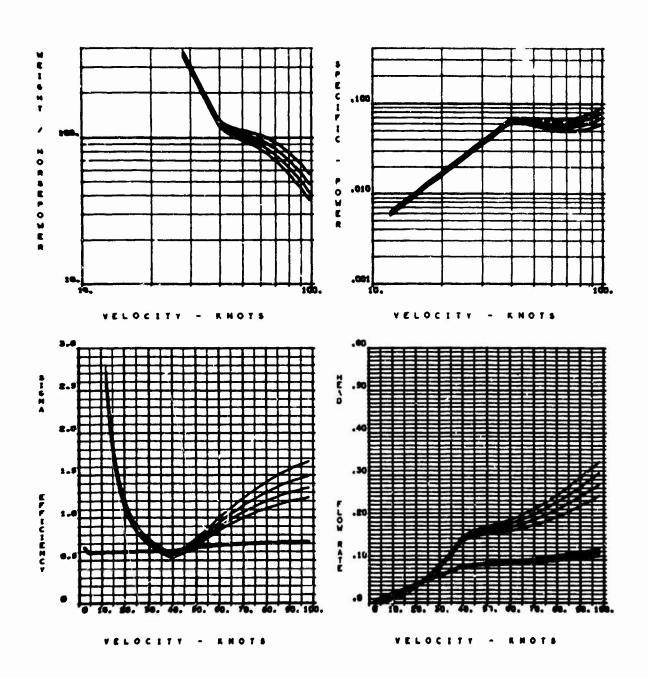
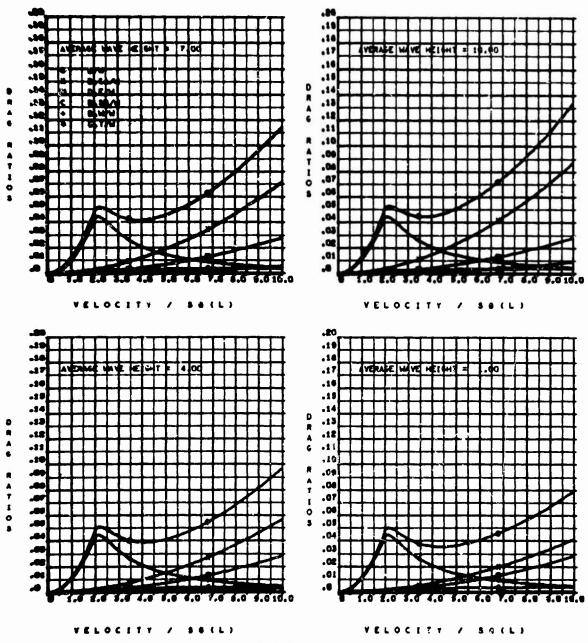


Figure 12 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 12 (Continued)
(b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

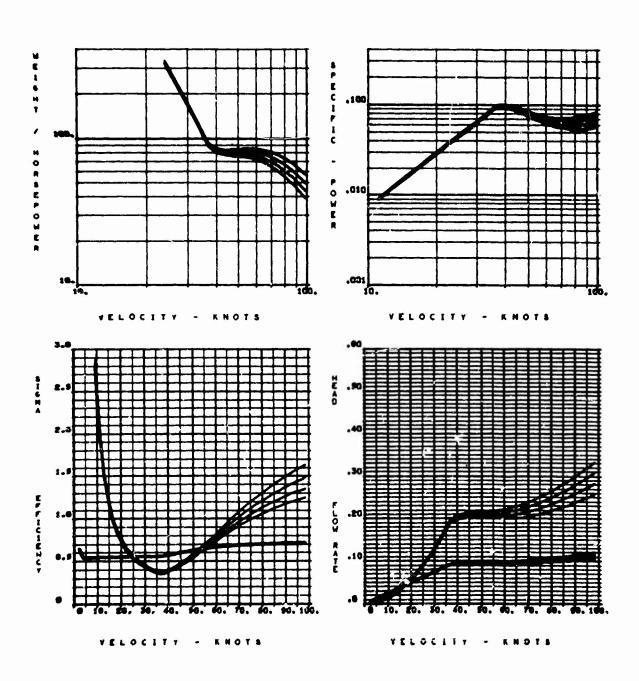
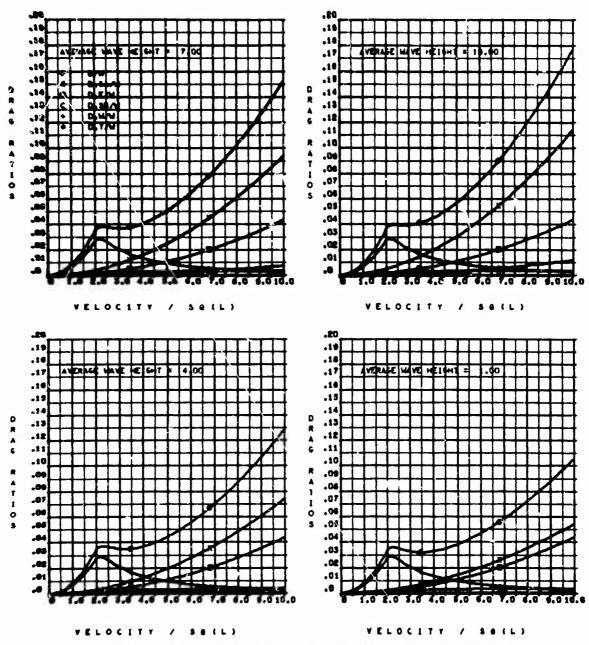


Figure 12 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 12 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{S} = 1.1$

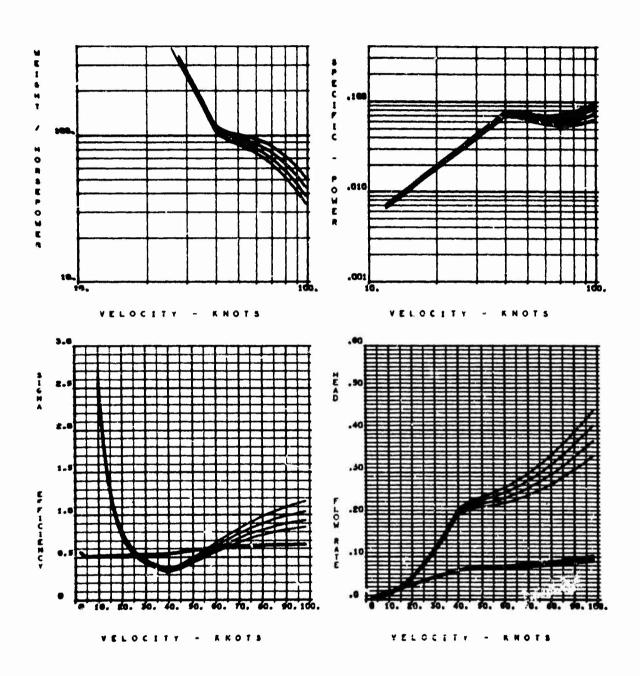
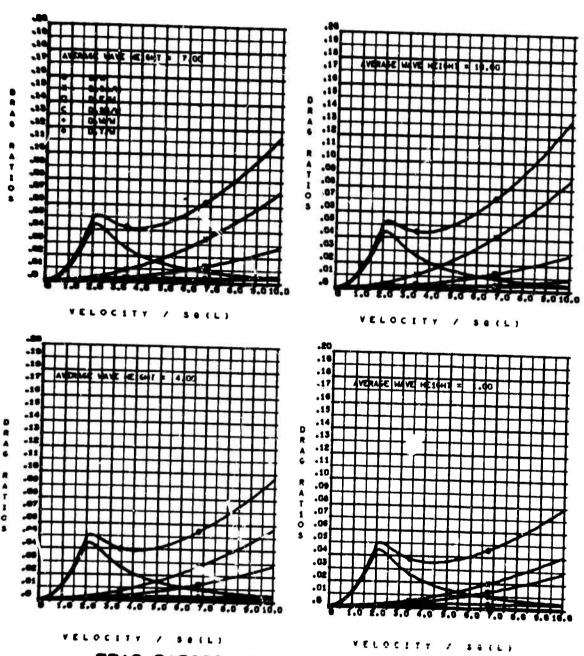


Figure 12 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 12 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

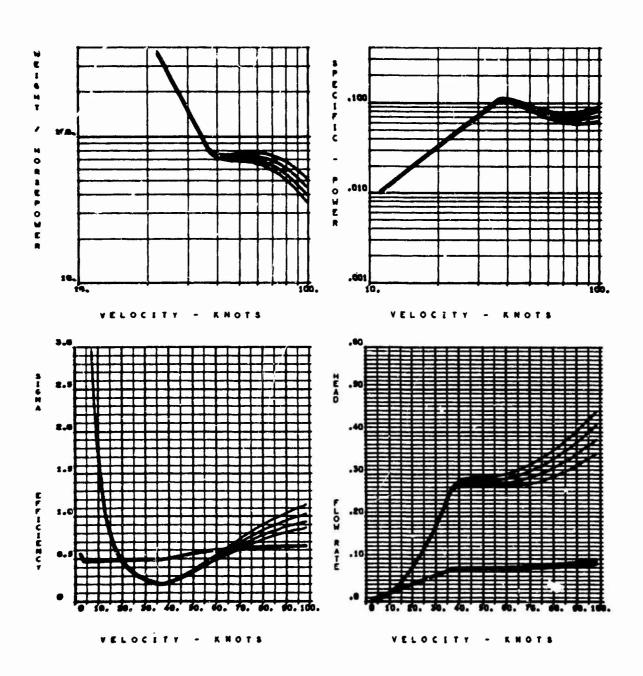
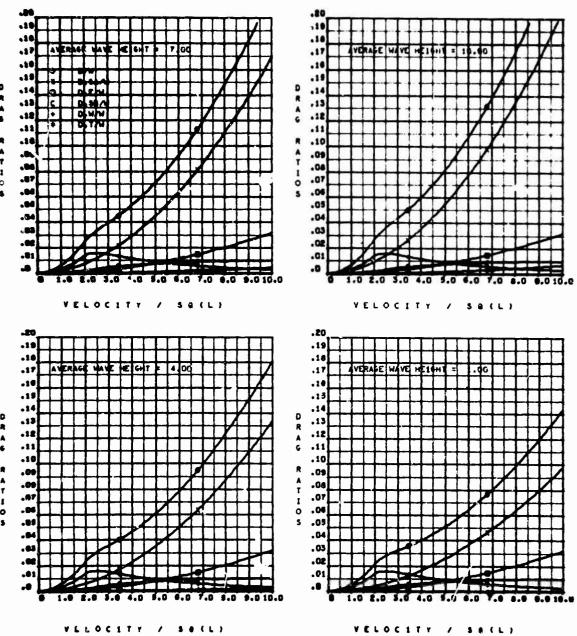


Figure 12 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 13 - General Performance Parameters of 10,000 Ton CAB With $\ell/b = 3.74$

(a)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

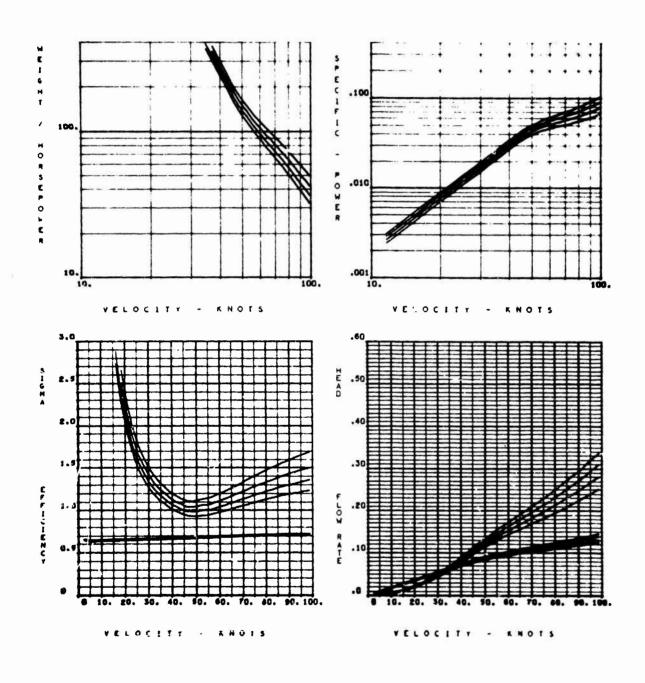
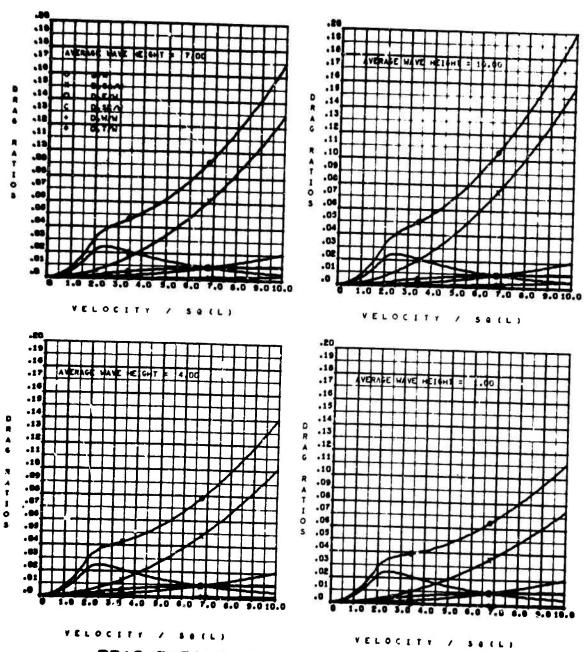


Figure 13 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 13 (Continued)
(b)
$$K_{D_{S}} = 0.04$$
, $K_{D_{S}} = 0.08$, $w/\sqrt{S} = 1.7$

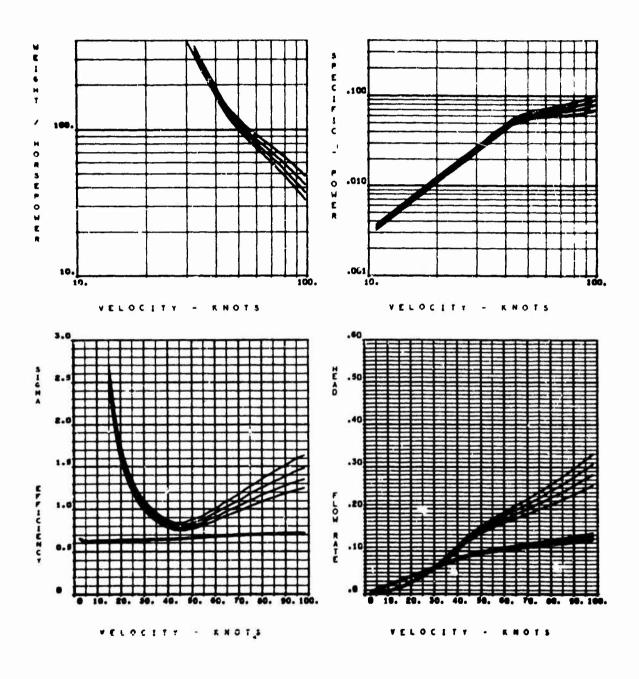
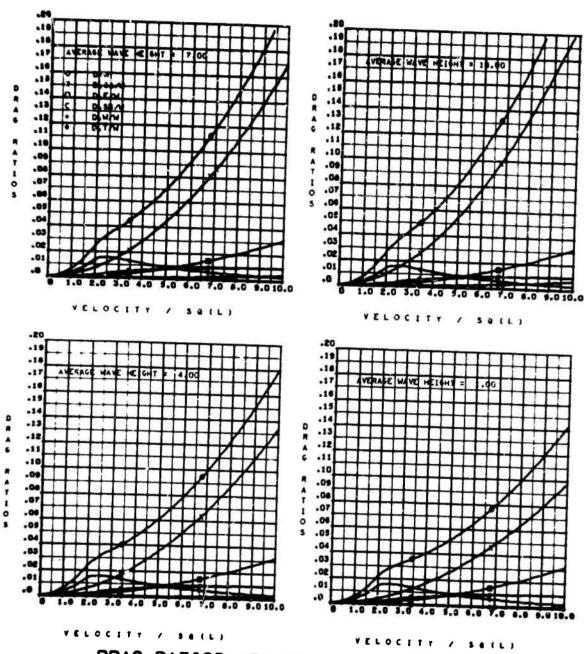


Figure 13 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 13 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.1$

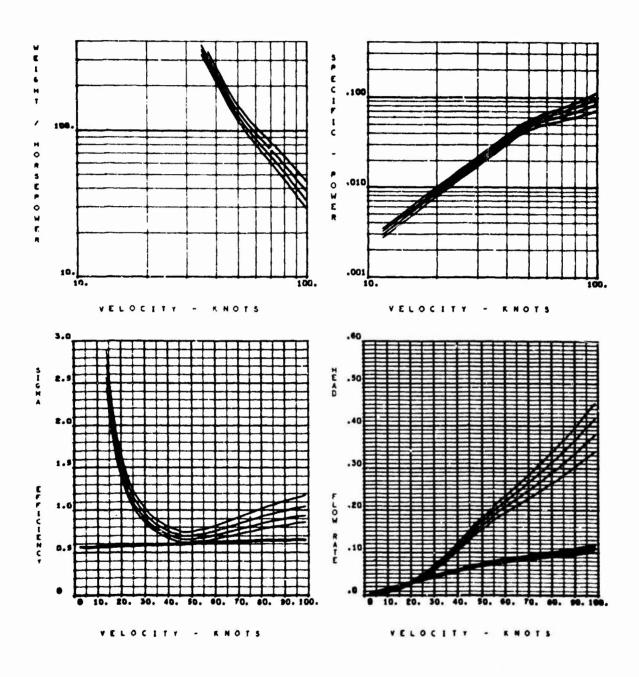
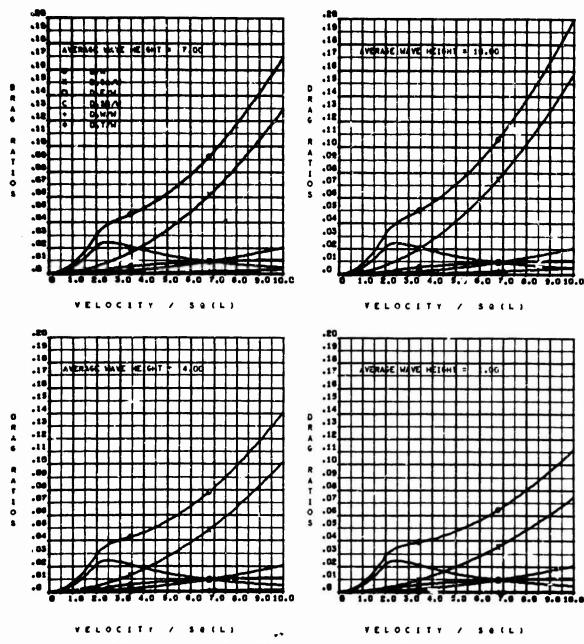


Figure 13 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 13 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

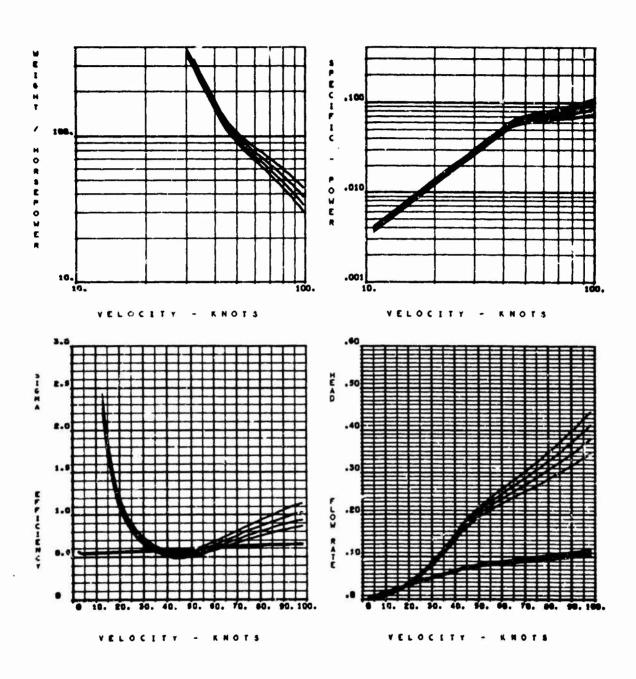
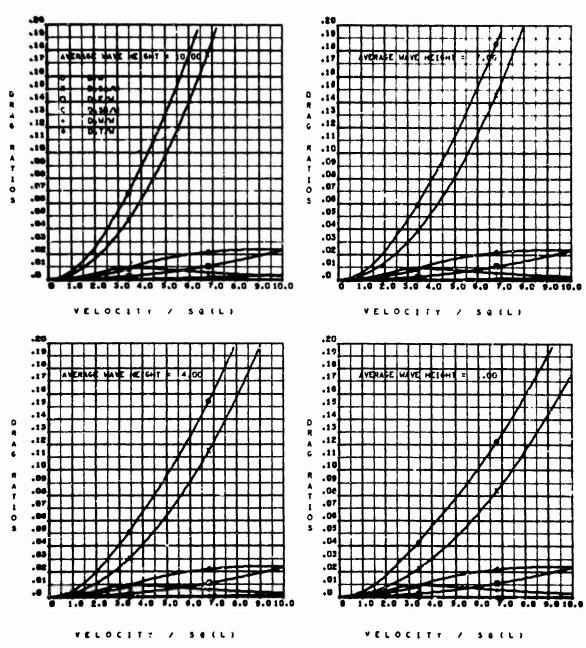


Figure 13 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 14 - General Performance Parameters of 10,000 Ton CAB With $\ell/b = 7.0$ (a) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

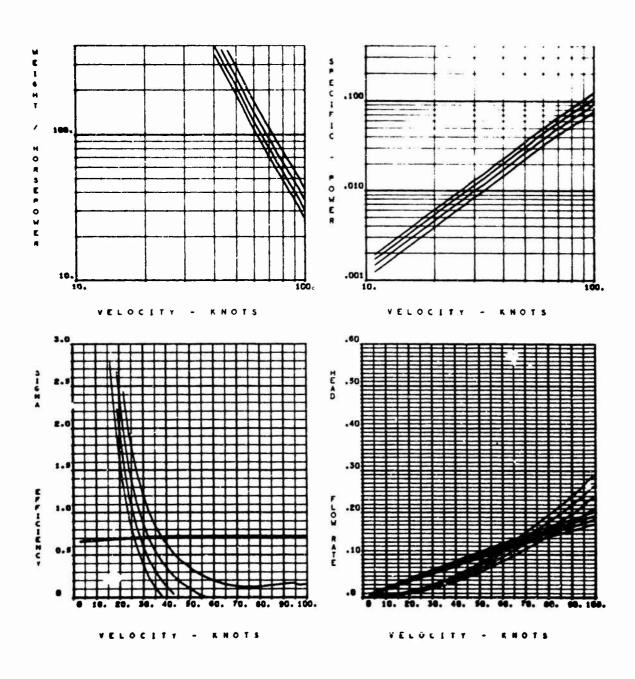
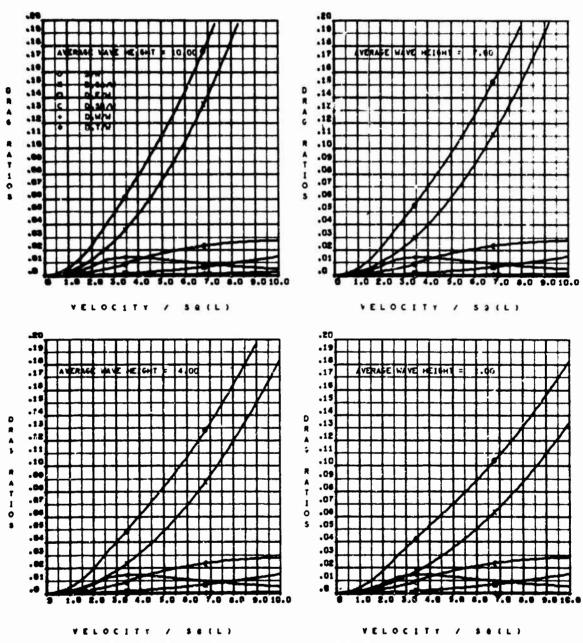


Figure 14 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 14 (Continued)
(b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

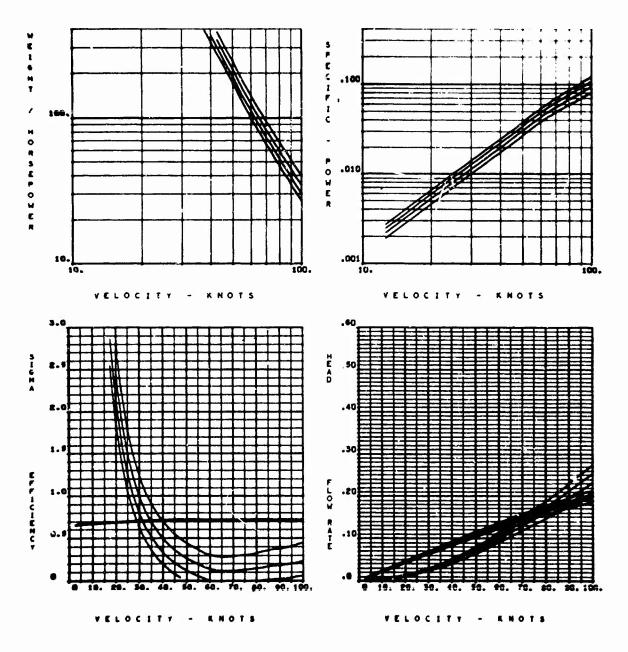
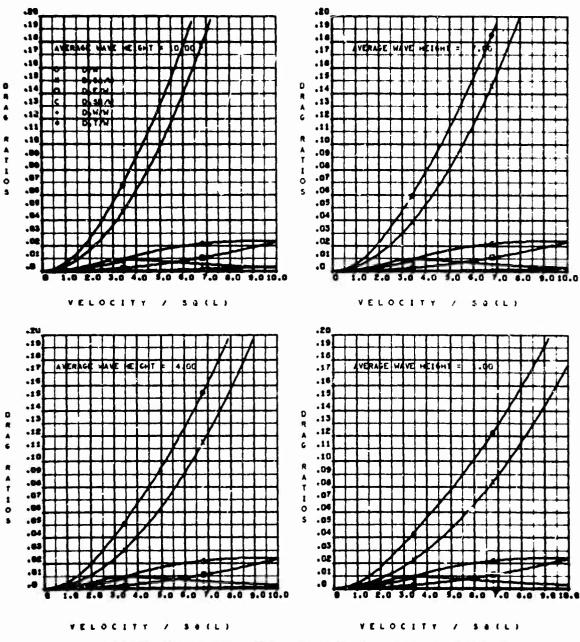


Figure 14 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 14 (Continued)

(c)
$$K_{D_D} = 0.08$$
, $K_{D_S} = 0.16$, $w/\sqrt{S} = 1.1$

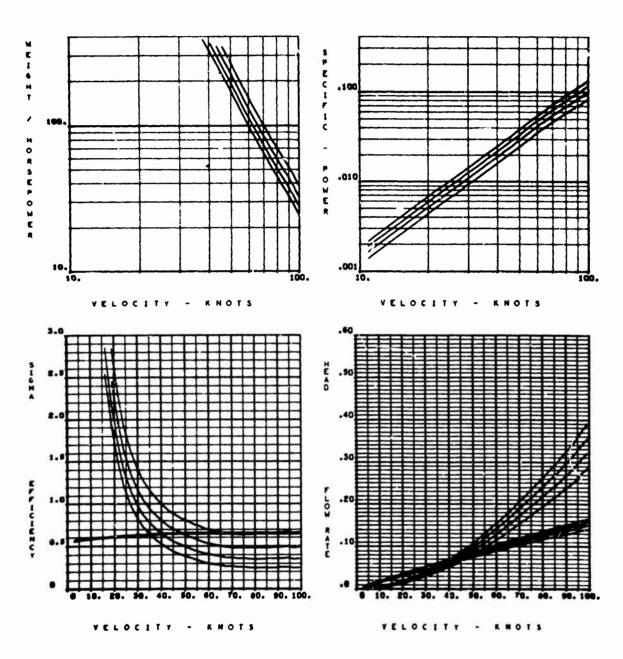
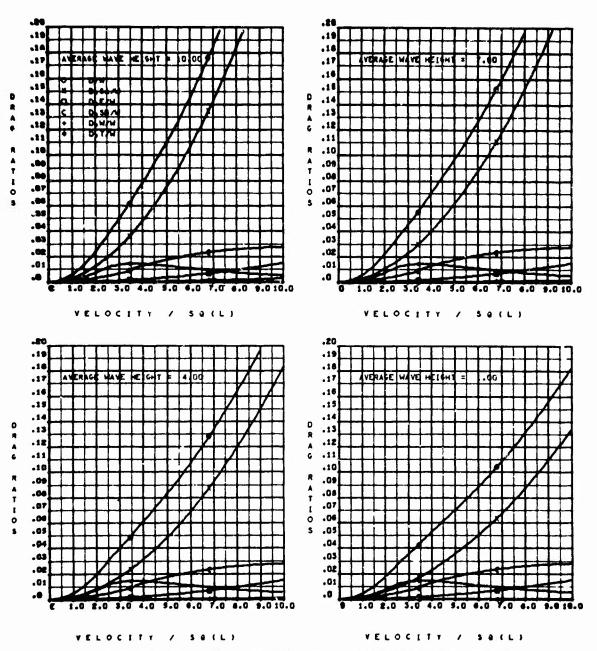


Figure 14 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 14 (Continued)
(d) $K_{D_{S}} = 0.08$, $K_{D_{S}} = 0.16$, $w/\sqrt{s} = 1.7$

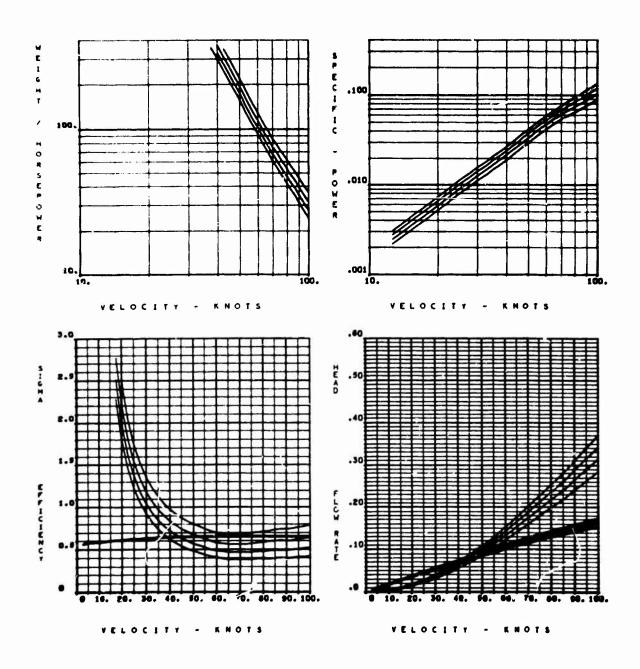
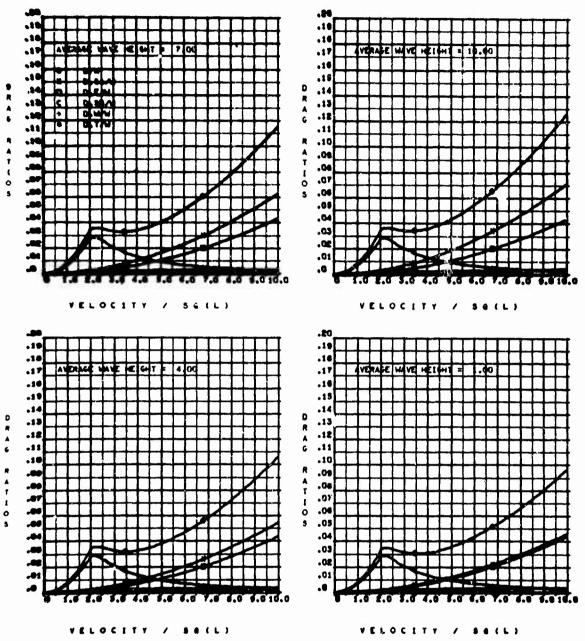


Figure 14 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 15 - General Performance Parameters of 100,000 Ton CAB With ℓ/b = 2.0

(a)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

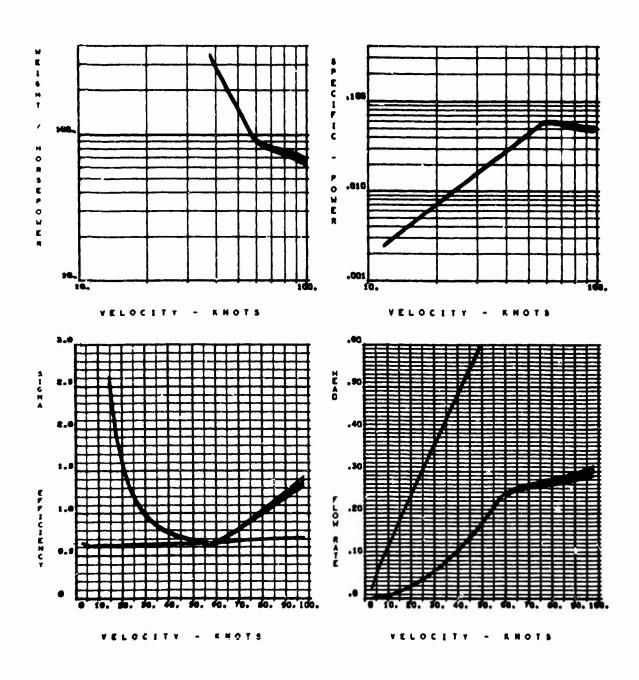
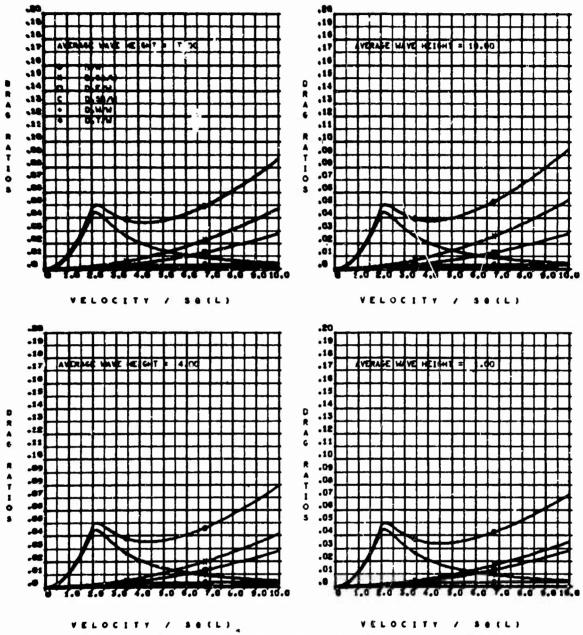


Figure 15 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 15 (Continued)
(b) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

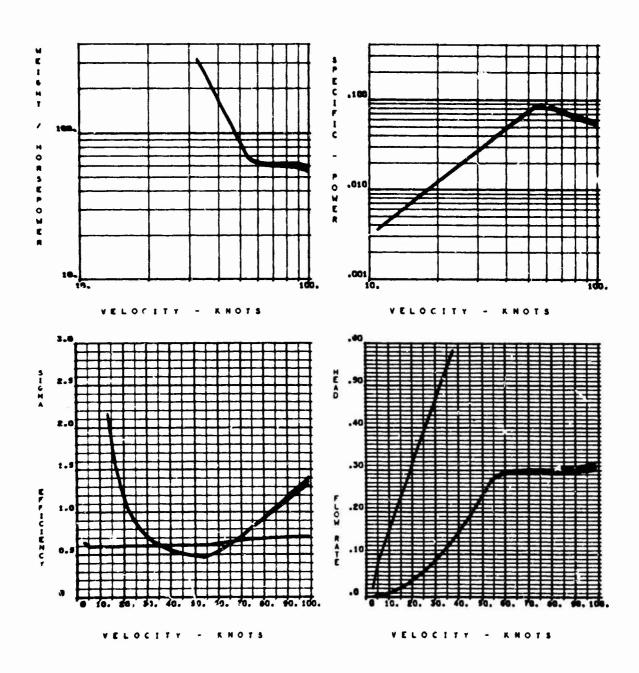
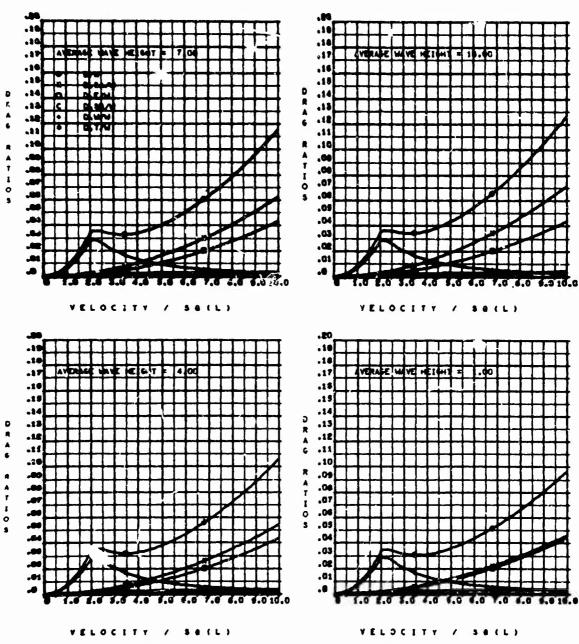


Figure 15 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 15 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.1$

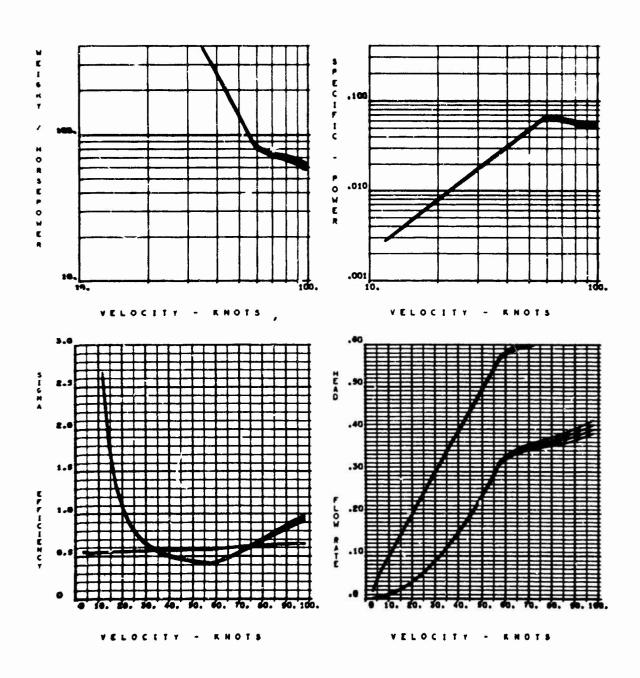
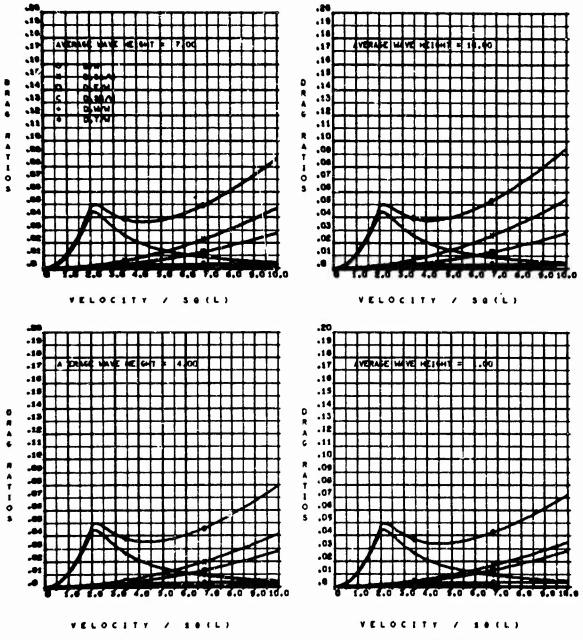


Figure 15 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 15 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

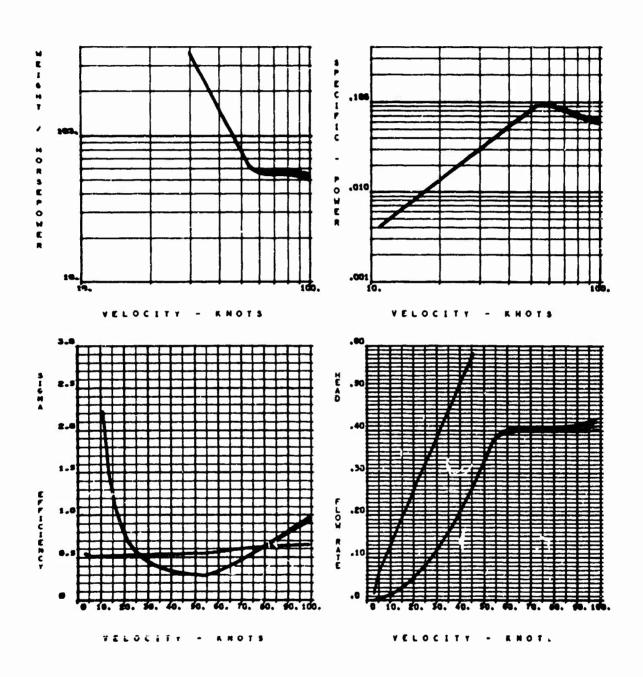
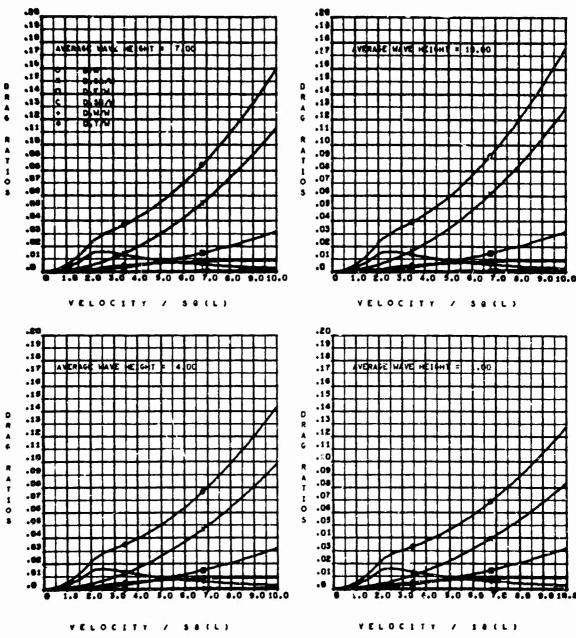


Figure 15 (Concluded)
(d) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 16 - General Performance Parameters of 100,000 Ton CAB With $\ell/b = 3.74$ (a) $K_{D_D} = 0.04$, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.1$

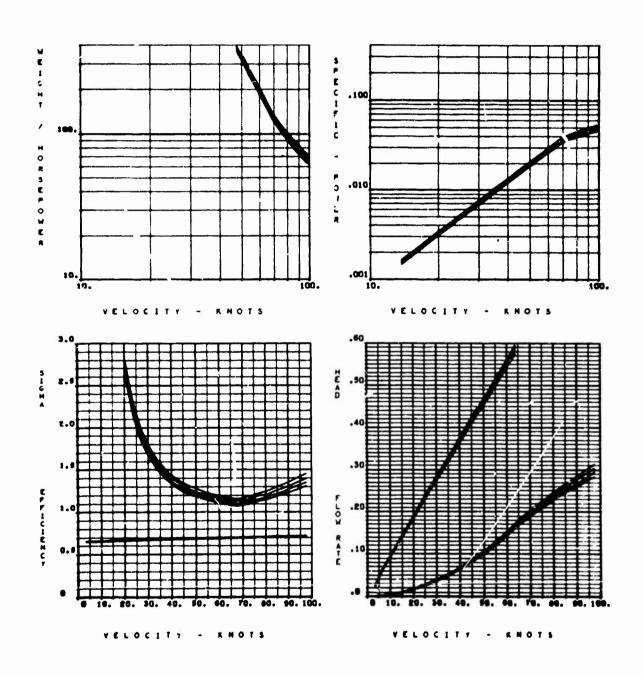
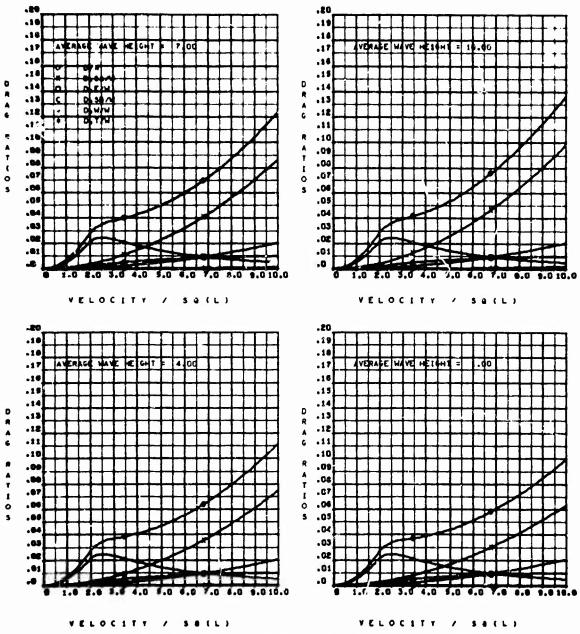


Figure 16 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 16 (Continued)
(b) $K_{D_{D}} = 0.04$, $K_{D_{S}} = 0.08$, $w/\sqrt{S} = 1.7$

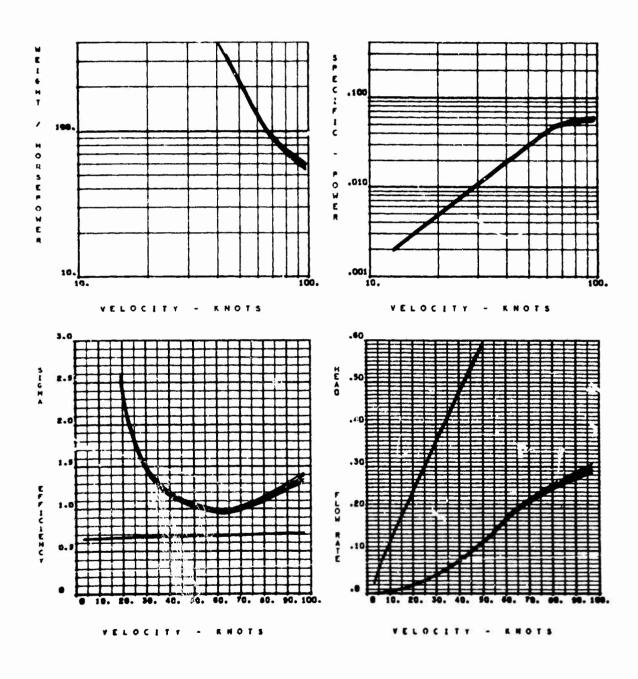
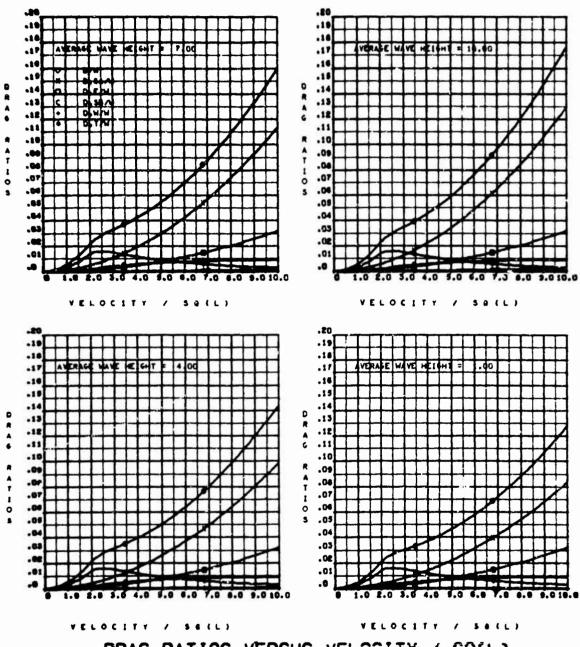


Figure 16 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 16 (Continued)
(c) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.1$

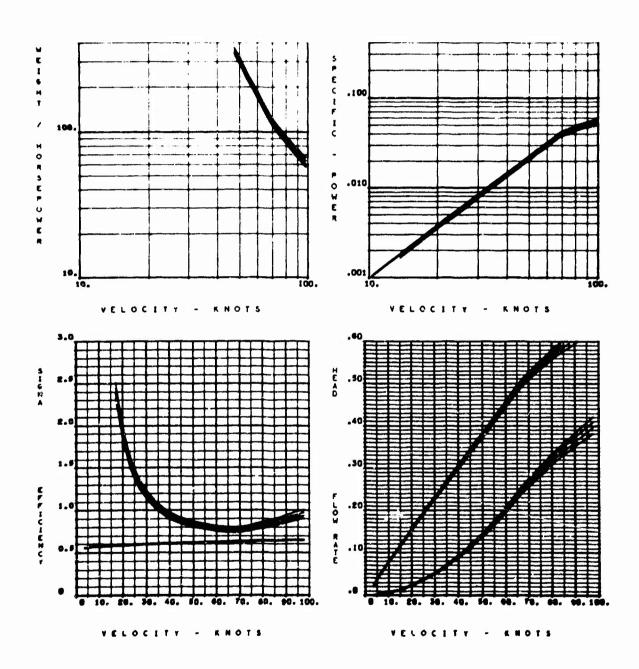
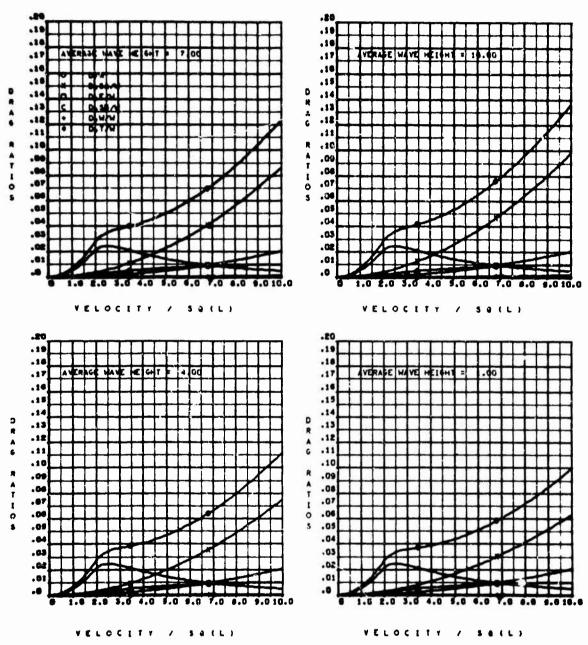


Figure 16 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 16 (Continued)
(d) $K_{D_D} = 0.08$, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$ -106-

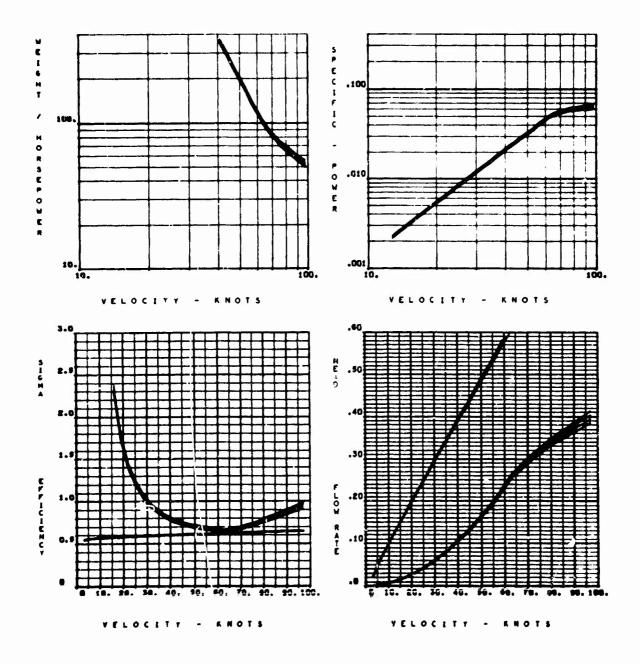


Figure 16 (Concluded)
(d) Concluded

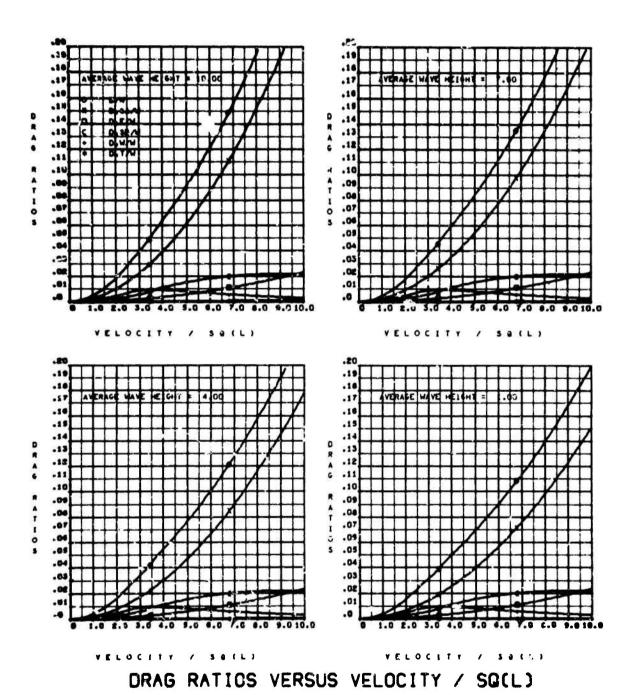


Figure 17 - General Performance Parameters of 100,000 Ton CAB

With 1/b = 7.0

(a)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w/\sqrt{S} = 1.1$

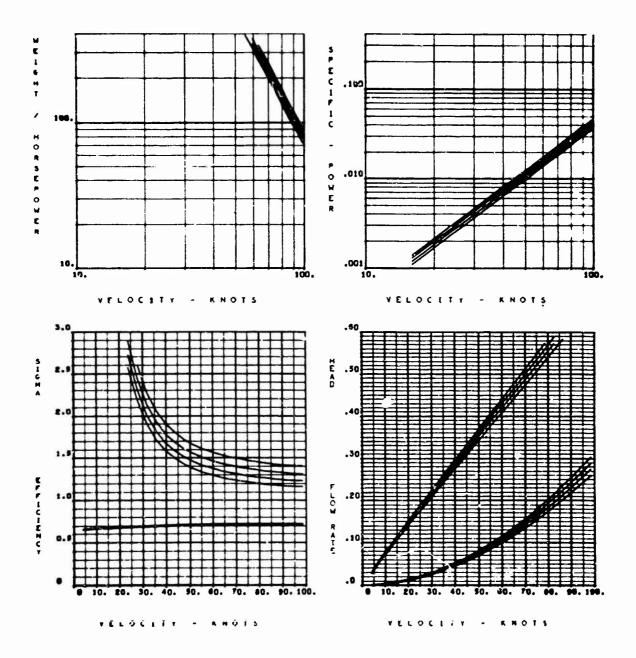
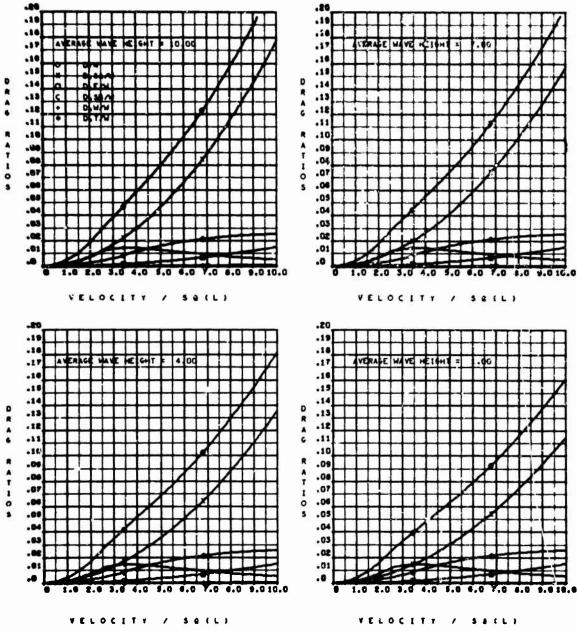


Figure 17 (Continued)
(a) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 17 (Continued)
(b)
$$K_{D_D} = 0.04$$
, $K_{D_S} = 0.08$, $w/\sqrt{s} = 1.7$

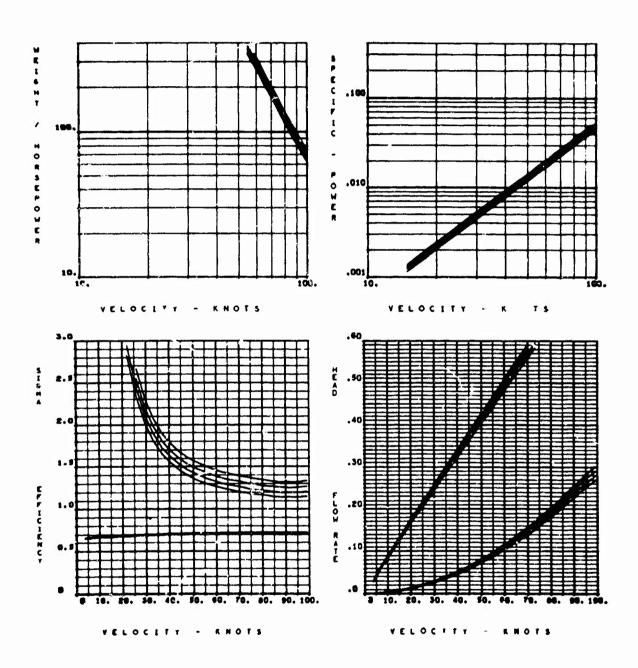
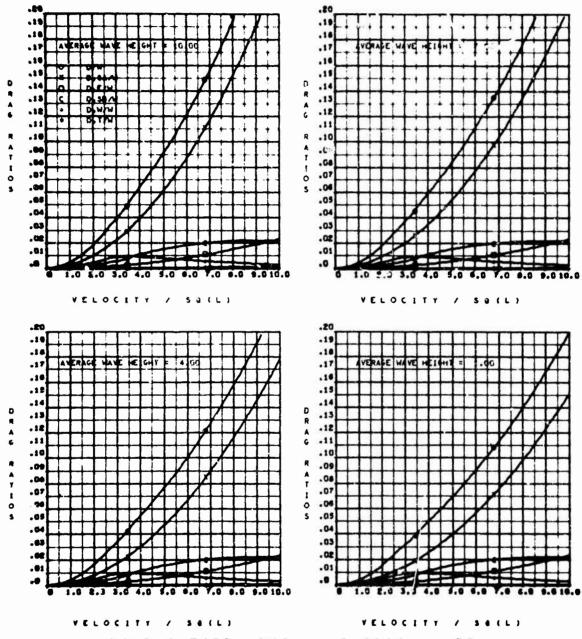


Figure 17 (Continued)
(b) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 17 (Continued)
(c) K_D = 0.08, K_D = 0.16, w/\sqrt{S} = 1.1
-112-

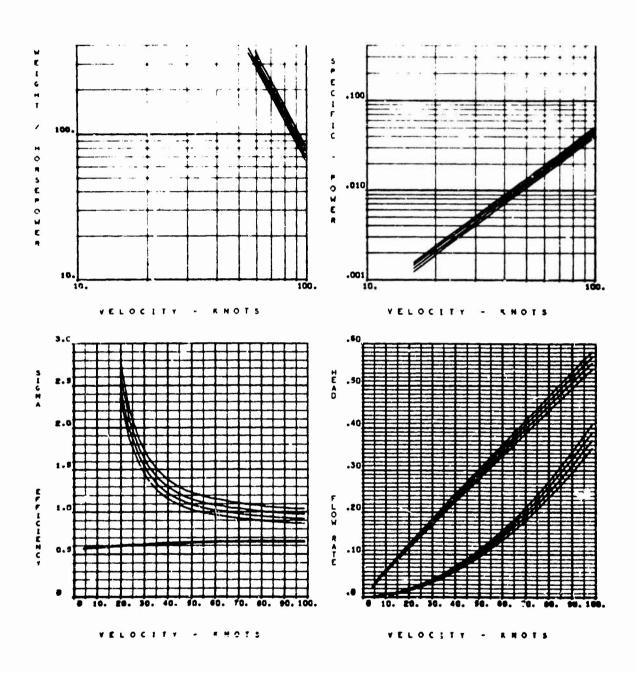
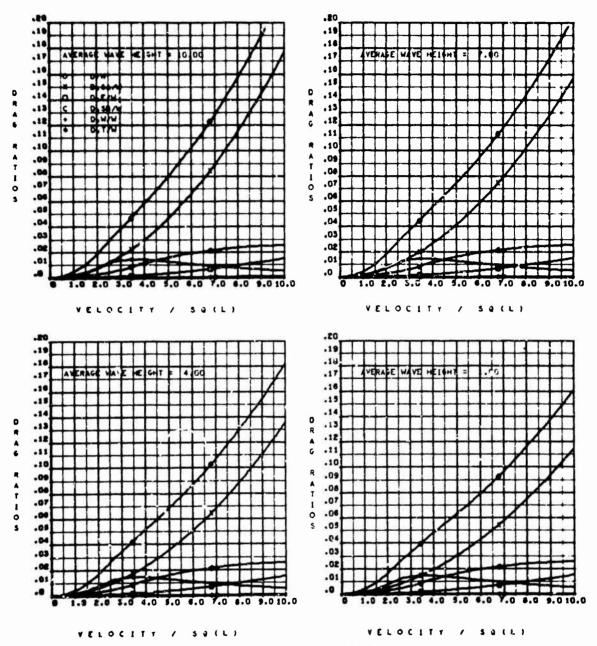


Figure 17 (Continued)
(c) Concluded



DRAG RATIOS VERSUS VELOCITY / SQ(L)

Figure 17 (Continued)
(d)
$$K_{D_D} = 0.08$$
, $K_{D_S} = 0.16$, $w/\sqrt{s} = 1.7$

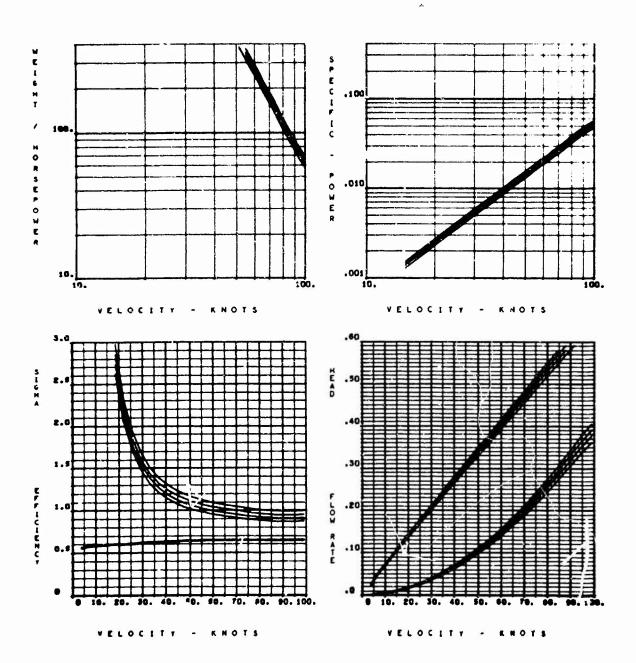


Figure 17 (Concluded)
(d) Concluded

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4 DESCRIPTIVE NOTES (Type of report and inclusive detas)						
S AUTHOR(S) (Lest name, first name, initial) Williams, Robert M.						
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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY					
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	Washington, D. C. 20360					
13 ABSTRACT						

Performance predictions of Captured Air Bubble (CAB) vehicles utilizing water jet propulsion are presented. The analysis was made for various combinations of gross weight, specific loading, length-tobeam ratio, and wave height. In addition, the effect of varying the

ducting loss coefficient has also been investigated.

It was found that the total drag "hump" of low length-to-beam ratios (1/b) was eliminated at higher 1/b values. This effect is due to the complex behavior of the wavemaking drag component. It was further found that for a particular length-to-beam ratio (1/b) a value of specific cushion loading existed which optimized the performance (as messured by the ratio of weight to horsepower required). The lighter specific cushion loadings offered definite performance advantages at the lower length-to-beam ratios.

DD . FORM 1473

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KEY WORDS		ROLE	wT	ROLE	WY	ROLE	WT
CAB Vehic	le.						
Surface E	ffect Ship						
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Water Jet	Propulsion						
Efficienc	,						
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